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SAN ANDREAS RIFT IN SOUTHWESTERN CALIFORNIA

BAILEY WILLIS
Stanford University

ABSTRACT

That portion of California which lies southwest of the San Andreas Rift and south of the San Bernardino and San Gabriel ranges, generally known as the Los Angeles region, is described according to the evidences of physiographic and structural facts, so far as they are available. The structures are considered to be effects of shearing in massive rocks, especially controlled by bodies of intrusive granodiorite. The shearing is accompanied by intense compression, and stratified rocks are folded, but folding is not the primary structure. The analysis of the stresses results in the recognition of a rotational movement of the entire mass of the region, and the San Andreas Rift appears as a strike-slip fault between the batholith of Lower California and the pre-Cambrian element of southeastern California. The shearing is analyzed according to mechanical principles, and deductions are made as to the origin of the stress. The dominant stress is found to have been oriented from south toward north. Several hypotheses are presented to account for it and, while none is regarded as established, that which deduces the pressure from the dynamic energy of the batholiths through metamorphism of crystals appears to have the best chance of survival.

DEFINITION OF AREA

That part of southern California which lies between the Pacific Ocean and the desert ranges, forming the southwestern corner of the state, is topographically and geologically a distinct unit, characterized by a local geologic history and a special structure. In form it may be described as an oblong, roughly 150 miles long from southeast to northwest and 100 miles wide. The northeastern corner is rounded off.

The geologic formations may be broadly grouped in three categories, namely: (1) the oldest, comprising metamorphic rocks of pre-Triassic age and possibly Trias; (2) intrusions of a general

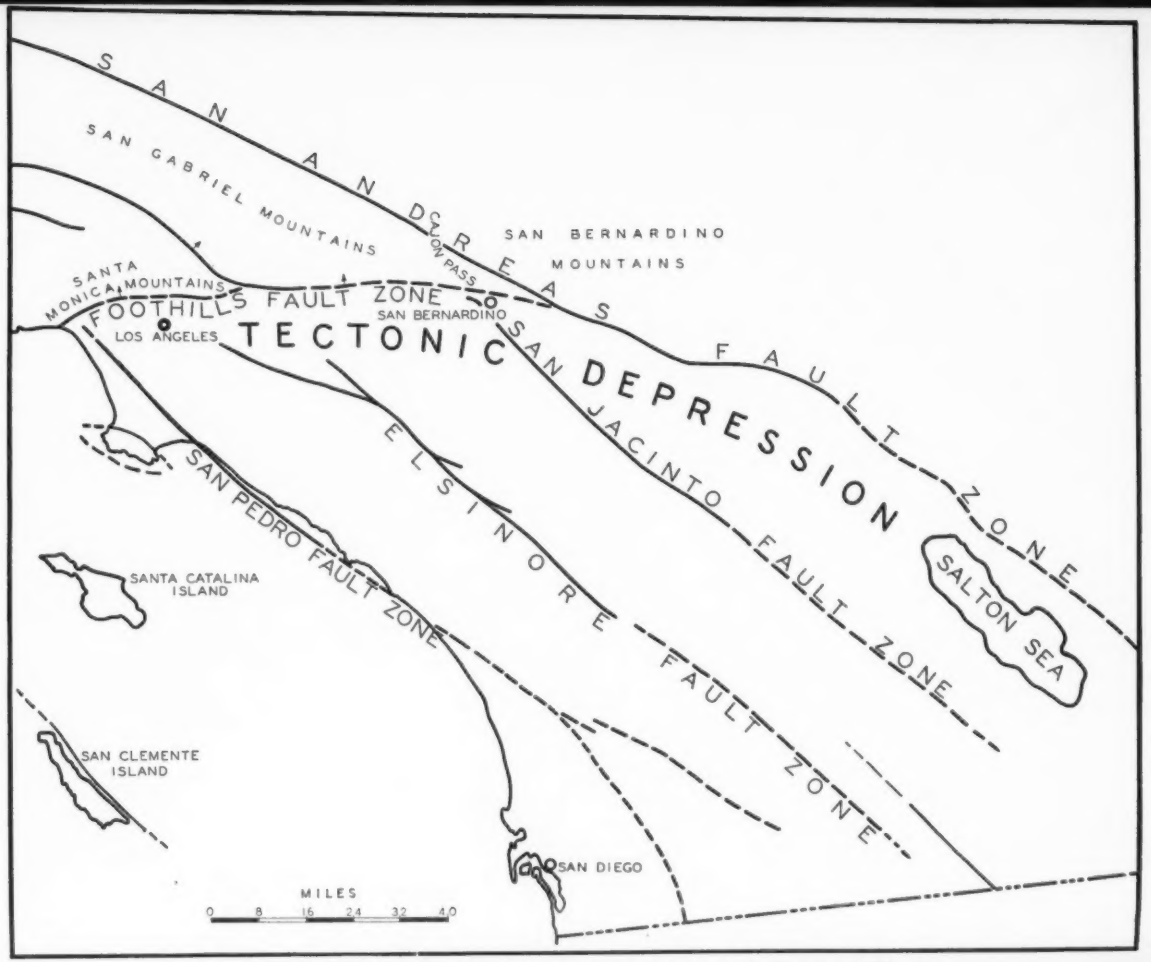

FIG. 1.—Skeleton diagram of the major structural features of southwestern California

granodiorite facies and of late Mesozoic age; and (3) Tertiary and later sediments. In this discussion attention is focused on the granodiorite masses, particularly with reference to their influence upon the structural development of the region. Certain structures resulted directly from the magmatic intrusions; certain others are interpreted as effects of stresses transmitted by the massive rigid bodies during the ages since elapsed. All the rocks, from pre-Triassic to Recent, have been displaced by the tectonic movements, and we are here concerned primarily with the mechanical effects of displacements of the more or less inflexible masses.

The oldest rocks are metamorphosed sediments. The basement upon which they were laid down is not yet identified, so far as I know. It may have been oceanic floor or peneplain and of any age from Trias back to pre-Cambrian. But the crustal segment that is southwestern California constitutes a relatively young, marginal strip of the continent, which was added to the Pacific Coast of North America in late Mesozoic time by intrusions of granodiorite. In this genetic characteristic the area is a direct continuation of the peninsula of Lower California. The long orogenic, in contradistinction to epeirogenic, batholith of that continental spur here impinges against the ancient, pre-Cambrian element of the continent that forms southeastern California and western Arizona.

The boundary between the old land and the newer is a fault zone, known as the San Andreas because it is continuous as a zone of displacement with the fault of that name, which traverses the San Andreas Valley near San Francisco. Perhaps it may be as well to remark that the continuity of the great fracture for more than 500 miles does not, in my opinion, necessarily imply identity of dynamic conditions throughout the whole length of the fault. The great rift is not a simple structure. It is probably made up of several segments, one of which has been described in a preceding article on the San Andreas Rift in central California.[1]

The southern stretch of the San Andreas fault zone, with which we now have to deal, reaches from the Gulf of California northwestward about 300 miles to the cross-range of the Tehachapi

[1] Bailey Willis, "San Andreas Rift, California," *Jour. Geol.*, Vol. XLVI (1938), pp. 793–827.

FIG. 1.—Skeleton diagram of the major structural features of southwestern California

Mountains, where a continuation of it turns westward round the southern end of the Central Valley of California. Only the southern half of this stretch, extending from the Gulf of California to north of San Bernardino, between latitudes 32° 30′ and 34° 30′, bounds southwestern California, but for that distance of 150 miles it forms the northeastern outline of the area.

The northern limit of this crustal segment of southwestern California is here assumed to be marked by the San Gabriel Range and Santa Monica Mountains. Or perhaps, better said, the two ranges constitute the frame enclosing the area along the northern side, and the Foothills fault, which skirts their southern base, is the actual boundary. We shall describe these east-west trending ranges and their structural relations in some detail. It will here suffice to state that they are arched up to altitudes ranging between 5,000 and 8,000 feet and that a Pliocene peneplain crowns the arches. That is to say, they are post-Pliocene uplifts of great magnitude.

The visible southwestern boundary of the land area we are defining is the Pacific Coast in the extent from San Diego to Santa Monica. The limit is purely accidental, being determined only by the contour of sea-level against shore features that vary in character from sand beaches to bluffs due to wave erosion along higher sections. Beyond the contour seaward the general geologic structure of the land extends to the sea bottom. This appears in a well-known fault which traces the northeast scarp of San Clemente Island, 60 miles west of the parallel San Pedro fault zone, and which like the similar faults of the mainland is an earthquake generator. Thus we must include a more or less considerable section of the sea bottom in the structural unit of southwestern California. It is convenient, and probably as nearly in accord with fact as our knowledge of facts permits us to come, to draw an outer limit along the continental slope, about 100 miles offshore. This doubles the diameter of the segment in the northeast-southwest direction. We have, however, very little knowledge of the structure of the sea bottom, beyond the suggestions of faults and uplifts indicated by the troughs and islands. This discussion will be confined to the facts observed within the land area.

An arbitrary southern limit to the area to be discussed may be

adopted along the Mexican boundary. But it should not be forgotten that Lower California is the major part of the geologic province, of which southwestern California is the smaller, northern section, and that we are comparatively ignorant of essential structural and dynamic conditions in the larger mass. It will appear that we have to look there for the source of a force exerted from the south upon the California segment.

Having thus defined the area to be discussed, we may note its landscape features. They are of prime significance in any attempt to analyze the structure, since the faulting is more often to be recognized in displacements of peneplains than in abnormal relations of strata.

The mountain ranges of southwestern California are surprisingly high and surprisingly young. The well-known Pliocene peneplain or matureland, as it may more accurately be described, cannot have had any very notable elevation above sea, when the valleys were widened to flat plains. Hence when these valleys occur, as they do, in the summits of mountains at altitudes of 5,000–8,000 feet or more, the proof of post-Pliocene elevation is conclusive. The old landscape included groups of hills and individual monadnocks that rose 1,000 feet or more above the valleys and these now constitute the dominant peaks, 10,000 feet and upward above sea.

Occurrences of the Pliocene matureland at various altitudes above sea will be cited in describing the ranges. It will be found that the criteria by which it may be identified are consistent, though the elevations differ, and that use of the peneplain to interpret fault movements and also uparching and tilting is of material service.

One has, however, to be on one's guard against misinterpretation. Faulting has progressed vigorously since Pliocene time. That is true. But uplifts and warping, not necessarily accompanied by faulting, have rejuvenated old valleys and initiated new ones with all the striking effects produced by erosion during Pleistocene epochs of greater or less precipitation. Streams adjusted to outcrops of schist not infrequently develop steep slopes which resemble fault scarps and may be erroneously classified as such.

There is another effect of erosion which has frequently been misinterpreted. It is the steep slope descending to a known fault. In

the past it has been a not uncommon assumption that the slope at least approximated the angle of dip of the fault, or that the mountain slope and the fault plane dipped in the same direction. This subconscious assumption has been linked with the general idea that the major faults are normal, gravity faults. But it has been shown by recent studies, such as that of Mason Hill on the San Gabriel Range, that a mountain mass which rides upon a thrust plane may present a front that closely resembles an eroded fault scarp rising from a vertical shear or even from a true gravity fault. Distinguishing features, such as adjustment to weak rocks in case of erosion pure and simple or remnants of an identifiable fault plane in case of normal faulting, may characterize a mountain face. But where definite criteria are lacking, the character of any slope is indeterminate.

GENERAL STRUCTURE

Southwestern California, together with the framework of mountains surrounding it, presents three major structural elements: the framework, a profound tectonic depression, and the central mass.

The framework comprised several distinct ranges which are neither continuous nor parallel. Along the northern side of the area stretch the Santa Monica and San Gabriel, as already stated. The San Bernardino is a height that also trends nearly east and west, but for that reason diverges eastward from the boundary fault, the San Andreas. The angle between the structural trends of the range and the fault approximates 30°. Farther south, beyond less well-defined heights of the Little San Bernardino Range, the divergent strike appears in the tectonic valley east of Thermal and in the Orocopia-Chuckwalla Mountains south of that valley. Farther south the Chocolate Mountains are delineated on the available maps as paralleling the San Andreas fault. It must be said, however, that topographical and geological maps of this desert region are very inadequate, and only major features can be suggested.

The basic structure of the ranges in the framework, so far as it is definitely known, is marked by thrust planes that dip under them. They may be regarded as having been pushed southward or southwestward on overthrusts or as being underthrust from the opposite

direction. The displacements are known for the Santa Monica and San Gabriel ranges and are inferred with probability for the San Bernardino. The structural boundaries of the Orocopia-Chuckwalla and Chocolate mountains are not known. It seems probable they are of similar character.

Relatively low passes align between these heights. They are valleys, extending eastward from the San Andreas fault zone, and their tectonic character as relatively depressed or lagging strips, is indicated by the presence of remnants of the Pliocene matureland surface along their sides, above Pleistocene canyons but far below the residuals of the same surface in the mountain summits. In antiquity they served to locate Indian trails. Now they are followed by highways, and through one of them, the one east of Thermal, passes the Los Angeles–Colorado River aqueduct.

Within the tectonic rim of mountains and passes stretches the second major structural feature of southwest California, a long depression. It is composed of a number of sections, which may be enumerated as follows: Imperial Valley, Salton Basin, Coachella Valley, San Gorgonio Pass, San Bernardino–Pasadena Basin, and Los Angeles Basin. The arc of low valleys and basins on land is continued in submerged stretches, the Gulf of California to the south and the Santa Barbara Channel to the west.

On the land the elevations of the actual valley floors vary between 2,500 feet above sea at Beaumont at the western entrance to San Gorgonio Pass and something more than 250 feet below sea-level in the Salton Basin. As the depression is filled with Recent and Pleistocene sediments to a variable, but generally considerable depth, our datum plane, the Pliocene matureland, lies below these actual surfaces. The differences of altitude imposed upon it by uplift and lag, between mountain crest and buried valley bottom, are therefore greater than the topographic ones.

Marine waters hide the record of the conditions of the sea bottom beneath Santa Barbara Channel and the Gulf of California. Where the shores consist of marine beds of Pliocene or Miocene age, we may infer that they represent expansions of the contiguous sea. Where unconformities interrupt the Tertiary sequence, we may by inference extend land conditions seaward. But in general the details

escape us. We may say, however, with confidence, that the depressions occupied by the channel and the gulf have been zones of subsidence and deposition since a remote Tertiary or earlier time. A similar statement is true of the Los Angeles Basin, where the drill penetrates to early Tertiary strata and the metamorphic basement lies many thousand feet deeper.[2] It seems probable that Eocene and Cretaceous strata, which occur in the neighboring hills, lie buried in the depths.

The continuity of the trough between the Los Angeles Basin and the Gulf of California during Pliocene and Miocene times is indicated by Pliocene and Miocene deposits which appear where not covered by later formations. They are in part continental, in part marine. Recent researches[3] have shown that the depression was a marine strait, probably during middle Miocene, and that it antedates that period as a relatively low zone between highlands on either side. Nevertheless, its actual lag behind the uplifts of adjacent mountain ranges is of post-Pliocene development.

Within the depressed rim lies the central mass of southwestern California, a mountain region of strong relief which is dominantly due to sharp, vertical displacements.

We have already located the San Andreas fault zone as the outer boundary. Then comes the low margin. Within it the mountain ranges trend northwest-southeast and are defined by the San Jacinto, Elsinore, and San Pedro fault zones. There are three major faults and three strips, each of the latter being about 25 miles wide. The northeastern strip carries the San Jacinto Range which overlooks the Coachella Valley and San Gorgonio Pass, and is most strikingly developed toward its northern end. The central strip lies

[2] In April, 1935, Professors J. P. Buwalda and Beno Gutenberg, of the California Institute of Technology, reported briefly the results of seismic soundings in the Los Angeles Basin, at the meeting of the Cordilleran Section of the Geological Society of America. In response to an inquiry for further information, Dr. Buwalda courteously writes under date of March 26, 1936: "We have not published our results as yet because the interpretation of the geophysical data is difficult and some parts of it are not yet entirely certain. We are quite sure of some beliefs, however, for instance that the granite surface lies at a depth of about 45,000 ft. in the middle of the basin."

[3] W. P. Woodring, "Distribution and Age of Marine Tertiary of Colorado Desert," *Carnegie Inst. Washington, Pub. 418* (1931); R. A. Bramkamp, "Molluscan Fauna, Imperial Formation, San Gorgonio Pass," *Proc. Geol. Soc. Amer.* (1934), p. 385.

between the San Jacinto and Elsinore fault zones and is characterized by the plateau-like uplift of the Peninsula Ranges, which are high in the south and less continuous toward the north. West of the Elsinore fault rises the Elsinore Range, from which the land slopes in mountain spurs to the coast. Along and beyond the coast stretches the San Pedro fault zone, in greater part submerged and identified chiefly by the occurrence of earthquake foci along it.

This general sketch of the region having been presented, we may proceed to examine somewhat more in detail the critical structures upon which we must depend to arrive at an understanding of the possible mechanics and dynamics of their development. While the great tectonic depression is the main object of interest, the related uplifts are an essential part of the evidence. We begin with an account of the San Gabriel and Santa Monica ranges that form the northern rim.

SAN GABRIEL AND SANTA MONICA RANGES

A plain which stretches from east to west, from San Bernardino to Santa Monica, is the striking feature of the northern margin of southwestern California. It is the seat of a great population, centering in Los Angeles. Floored with silt and gravel from adjacent mountains, it is the surface of sedimentary deposits of fresh-water and marine origin that are exceedingly thick and extend back in age to early Tertiary or earlier times. Mountain ridges strike from southeast into this plain, but sink beneath it. None crosses it. Their crests are buried thousands of feet beneath the alluvium and older strata.

Along the northern margin of the plain stand the San Gabriel and Santa Monica mountains, rising 5,000–9,000 feet above it. In a northern climate the summits would be snow clad and the peaks would have been sculptured by glaciers; but in the warmth of latitude 34° snow lingers during the brief winter only, except in the shadow of the highest peaks. The mountain forms, in general, are broad; the masses are broadly arched; upon their wide surfaces stand the monadnocks of a preceding topographic cycle; in their arched slopes are cut the sharp ravines of the cycle initiated by

recent uplift. The canyons are very young, the uplift still in progress.

The San Gabriel and Santa Monica ranges, though aligned in similar positions north of the profound tectonic depression, are separated by the San Fernando Valley, which stretches between them, trending northwestward in a diagonal relation. They are thus distinct, though structurally similar elements, of the mountain barrier that dominates the Los Angeles–San Bernardino Plain.

The San Gabriel Range lies east of the Santa Monica. It has three principal lineaments, namely: (1) a southern mountain foot, along which it meets the plain; (2) a northeastern base, against the expanse of the Mohave Desert; and (3) a central, longitudinal fault which has located the canyon of the San Gabriel River. The southern boundary strikes east-west, the northeastern ranges northwesterly, and the central, San Gabriel fault splits the angle between the two.

The San Gabriel Range thus presents a sharp point toward the southeast. Its crest, rising in that direction and not far from the end carries the highest peak, Mount Baldy (10,080 ft. above sea), a monadnock on the Pliocene matureland. Mount Wilson, another monadnock, 5,886 feet in elevation and the site of the great observatory, stands above Pasedena in a central position on the range.

This spear-shaped mountain mass now presents the form of the uparched matureland, which in Pliocene time was flat and low. The uparched surface expresses an effect of intense internal shearing, which is further evidenced by the central, San Gabriel fault. The latter dips northeastward and may be regarded as an overthrust toward the south or an underthrust toward the north or as a combination of displacements in both directions. The last is probably the correct view, considering its medial position and the effects of action and reaction developed as the range was squeezed and raised between opposed stresses.

The San Gabriel Range is now recognized as a wedge-shaped mass, underthrust from both sides. The southern, east-west boundary, the Foothills fault, dips northward under the upthrust mountain. The northeastern basal fault, a lateral development from the San Andreas fault zone, dips southwestward under the range. Thus the

two thrusts dip toward each other like the sides of a wedge. The under side has more or less definitely that form, with the edge of the wedge 10 or 12 miles below the surface where the width of the top is 20 miles, on the assumption that the thrust planes are flat. It is more probable that they are curved, flattening toward horizontal or steepening toward vertical, according to the conditions of least resistance in the depths.

It is obvious that the structure and uparching of the San Gabriel Range can have resulted only from an orogenic pressure, directed approximately in a north-south bearing, in such a manner and with such intensity as to produce the two basal shearing planes, dipping at the surface approximately 50° toward each other. The swollen, uparched form of the surface and the internal thrusts, of which the central San Gabriel fault is the most prominent, demonstrate the effect of north-south shortening.

This interpretation of the underground form and internal structure of the San Gabriel Range is of very recent development. While it is true that the physiographic evidence suggested the structural interpretation to me in 1918, credit for the demonstration of the facts belongs entirely to Mason L. Hill and Levi P. Noble, whose independent, original, and definite observations are conclusive. The following quotations from their publications will serve to indicate to what extent the preceding generalizations are based upon their work.

Hill describes the somewhat limited area covered by his studies, enumerates the rock formations, which comprise the basement complex, Tertiary, and Recent, and critically analyzes the structures according to mechanical principles. He says in part:

> The area herein described lies near the west extremity of the range, about 18 miles north of Los Angeles. . . . . Elevations range from approximately 1,000 feet to more than 5,000 feet
>
> Two fault zones form the dominant structural features of the area. These zones trend in general slightly north of west. The northern is termed the San Gabriel zone and from south to north consists of the Watt, De Mille, and Dillon faults. The southern is called the Sierra Madre zone and from west to east consists of the Lopez and Sunland faults.[4]

[4] Mason L. Hill, "Structure of the San Gabriel Mountains," *Univ. Calif. Dept. Geol. Science Bull.*, Vol. XIX (1930), pp. 137–70.

Hill then proceeds to a detailed description of each of the faults and draws certain inferences from the facts bearing upon their relative developments as related, but sequential displacements. Under the heading, "Structural Mechanics," he continues:

Relations of stress to strain. It is assumed on the basis of apparent contemporaneity and similarity in type, as described and discussed above, that the structures are genetically related. Such a monogenetic, structural system is susceptible to mechanical interpretation of the relation stress to strain (structures). The following interpretation is suggested by the structures described in this paper.

The dip of the sub-parallel reverse faults (near 45°), parallelism of the Merrick syncline with the faults, and the dip-slip character of at least some of the faults (Lopez, Sunland, and Watt) taken together indicate stresses acting in a general NNE–SSW direction, predominately non-rotational in horizontal vertical planes, and with maximum relief vertical. . . . .

Assuming upward relief as more probable, the north-dipping faults are overthrusts and the apparent active stress is from the north. The absence of the south-dipping underthrust set is explained by the difficulty of downward relief. However, the assumption favoring upward relief is entirely a priori and since no evidence for overthrusting as contrasted with underthrusting is seen in the structure itself, no definite conclusion can be reached.

Passing over an interesting discussion of shearing versus folding in massive rocks, we proceed to quote Hill's conclusions:

Geologic history [of the San Gabriel Range]. (1) Plutonic invasion and intense metamorphism in pre-Cretaceous or early Cretaceous time.

(2) Uncovering of plutonic and metamorphic rocks by erosion, followed by deposition during Miocene and all (?) of Pliocene time.

(3) Late Pliocene or post-Pliocene deformation, blocking out the present range, with concomitant and subsequent erosion and deposition modifying the surface expression of the structural features.

Geologic structure. Heretofore the south front of the San Gabriel Mountains has been considered to be determined by normal faults. Part of this front, which appears to be in no way anomalous, is found to be characterized by reverse faults of late Pliocene or post-Pliocene age. These faults dip 30° to 70° northward with the granite and gneiss of the range relatively thrust over the folded Tertiary sediments to the south. The contemporaneity, orientation, and drag effects of the structures indicate predominantly non-rotational stress acting in a NNE–SSW direction. The deformation has effected both shortening of the earth's crust and relative elevation of the range above its surroundings.

Noble's intimate and thorough study of the section of the San Andreas fault zone north of San Bernardino, where it separates the

San Gabriel Range from the plateau of the Mohave Desert, has not been published as a monograph, and we have, outside of personal communications, to rely upon brief notes. They are, however, definite. We quote in part as follows:

> Southeasterly across the area [i.e., along the San Andreas Rift] runs a continuously traceable line of scarps, troughlike depressions, and ridges, which afford clear and unmistakable evidence of recent earth movements. This line of topographic features, which is so straight that one may sight along it for 25 miles or more, marks the position of a profound fault in the underlying rocks. The straight and continuous fault is the San Andreas Fault—unquestionably the master fault. Bordering the master fault is a belt of roughly parallel, branching, and interlacing fractures, which in places attains a width of 6 miles. . . . . The scarps, ridges, and depressions differ in no respect from the similar topographic features that mark the San Andreas fault where it has been described in the region north and south of San Francisco.[5]

After this introductory description Noble proceeds to describe in some detail the very recent, topographic evidence of displacements, mentioning in particular the relations that demonstrate strong horizontal movements. The strike-slip movements of that character are prevailingly such that the southwest side of the vertical fault has moved northwest past the northeast side, as is generally the case in the Coast Ranges. Where contrary strike slips are found they represent displacements of isolated blocks within the fault zone and may be attributed to the convergence of the minor lateral faults toward the northwest. Noble continues:

> The belt of interlacing and roughly parallel faults exhibits a structure so complex that a simple statement concerning it is difficult to make. In general the zone is a mosaic of elongated, sliver-like blocks, whose longer axes trend parallel with the main fault, but in many places the rock masses are so intricately shattered and different formations are mixed together that it is impossible to map them or to determine their relations and age. The evidence of the nature of the fault movements is somewhat conflicting; the dominant structure is a sort of slicing, which appears to be mainly the result of horizontal shear along the San Andreas Fault. No exposures of the fault plane are obtainable, but the straight course of the fault across the uneven topography suggests that it is nearly vertical. On the other hand the planes of a large number of faults in the fault zone are obviously thrust planes, nearly all of which dip southwest at angles ranging from 55° to vertical. These structures are the result of thrusting brought about by compressive forces acting from the southwest.

[5] L. P. Noble, "San Andreas Rift and Some Other Active Faults of Southeastern California," *Carnegie Inst. Washington Yearbook No. 25* (1925–26), pp. 415–28.

We may here note that Hill interpreted the thrusts emerging on the southern side of the San Gabriel Range as presumably due to forces acting from the northeast. Noble continues:

> A noteworthy feature of the zone is the occurrence of long, narrow blocks of granite, which form inverted prisms inset in soft Tertiary or early Quaternary beds by faulting, in such a way that the fault planes which separate the granite from the sediments dip under the granite prism from both sides, the apex of the granite pointing downward. Some of these granite blocks are a mile long and a quarter of a mile wide. This structure suggests that the granite blocks have been squeezed up by compression. Exposures of granite lying upon Tertiary or early Quaternary beds and separated from them by thrust planes that are almost flat are common in some parts of the fault zone.

It is evident that these wedge-shaped blocks of granite, sheared out in the fault zone itself, are miniatures of the far greater wedge of the San Gabriel Range.

We have quoted at some length from Noble on the character of the San Andreas fault zone where it crosses the northeastern front of the San Gabriel Range and terminates it structurally, although, as Noble says, it does not cut off the height abruptly. Continuing to cite his account and especially with reference to the thrusts, we note:

> Although the San Andreas fault [referring to the vertical, master shear] runs for some distance near the northern base of the San Gabriel Range, it does not actually bound the range, for it crosses at an elevation of 6,800 feet. The initial uplift of the range did not take place upon the main San Andreas Fault, but rather upon faults that branch from the San Andreas Fault Zone. The planes of these branching faults, wherever exposed to observation are thrust planes, which dip steeply southwestward into the mountain mass in such a way that the older crystalline rocks of the range override younger sedimentary rock at the base of the range.

This very explicit description leaves no doubt of the character and orientation of the thrusts along the northeastern side of the San Gabriel Range. They are overthrust from the southwest or underthrust from the northeast or thrust from both directions. We may repeat that the last named is probably the correct interpretation. Since the displacements are contemporaneous with those that Hill describes and opposed in dip, Noble's observations confirm Hill's conclusions as to the mechanism of uplift by compression of the wedge-shaped bock.

We pass to the Santa Monica Mountains, an uplift which in recent orogenic history and in position with reference to the Los Angeles Basin is a homologue of the San Gabriel Range in its relation to the San Bernardino–Pasadena depression.

The homologous relation between the two mountain ranges appears to me to follow from the occurrence of thrust faults which may be observed in road cuts in the hills north of Hollywood, dipping northward under the heights, and from their alignment along the northern side of the great depression. The internal structure of the Santa Monica Range is not, however, overthrust in the obvious manner described by Hill for the San Gabriel; and Hoots, to whom we are indebted for the survey of the former range, reflects in his interpretation the earlier view of the action of vertical forces.[6] We quote from *Professional Paper 165:*

> The eastern part of the Santa Monica Mountains . . . . is a large anticline that has experienced several stages of growth and deformation. . . . . In order to discuss satisfactorily the character and possible origin of the Santa Monica anticline and related structural features, it appears to be necessary to consider each individual period of pronounced diastrophism separately and to describe as accurately as possible the structural features which have resulted from each of these periods. There appear to have been at least three of such periods—the Jurassic (?) granitic intrusion, the middle Miocene disturbance, and the post-Miocene disturbance.

The last named is the one which has given the folded mass of the montain block its present form and elevation, as appears from the uplifted Pliocene valley in its central area and from the relation of the typical Pliocene matureland to the Pleistocene and Recent canyons in the outer slopes. Hoots writes thus of the post-Miocene deformation:

> It seems probable that the upper Miocene formation was deposited over most, if not all of the area covered by this report. As a result of post-Miocene uplift in the central part of the range the formation was folded to form an integral part of the Santa Monica anticline and has later been eroded from much of the crest and flanks of this large fold. . . . .
>
> [It is] suggested that this last period of folding resulted merely from a rejuvenation of the vertically acting forces that had earlier produced the Santa Monica anticline.

[6] H. W. Hoots, "Geology of the Eastern Part of the Santa Monica Mountains," *U.S. Geol. Surv. Prof. Paper 165* (1931), pp. 83–134; *16th Internat. Geol. Congress Guidebook 15, Southern California* (1933), pp. 40, 46.

This seems to be a somewhat unusual interpretation of the development of an anticline in sedimentary rocks. Hoots continues:

This folding was accompanied by considerable faulting in different parts of the area, but particularly along the south flank of the mountains. The slate near the southern base of the range is intricately distorted and appears to have undergone large scale deformation to a much greater degree than the overlying upper Miocene formation, although the slate in most other areas is characterized by simple structure. The upper Miocene here is broken by numerous short faults, which strike approximately parallel with the base of the mountains and most of which have displacements of not more than a few hundred feet and commonly considerably less. It seems probable that these small faults have resulted from post-Miocene movement along an older buried fault which parallels the base of the range.

The coastal area northwest of the city of Santa Monica is one of complex structural conditions and is composed of a series of small fault blocks, now largely concealed beneath Pleistocene alluvium. The faulting involved rocks of all ages from Cretaceous to Pliocene, and it appears that this belt is an integral part of the fault zone which parallels the base of the range and which is the result, in part at least, of deformation after Pliocene time.

The first movement which cuts across the mouth of Potrero Canyon occurred after the marine upper Pliocene or lower Pleistocene beds at the mouth of the canyon were laid down, but before the overlying uppermost Pleistocene alluvial-fan material was deposited. There is a suggestion in poor exposures in the east wall of the canyon that subsequent movement has displaced the late Pleistocene alluvial-fan deposits about 25 feet. The strike of this fault is in perfect alignment with a pronounced terrace in the surface of the late Pleistocene alluvial plain east of Potrero Canyon, a terrace which may be traced eastward to Santa Monica Canyon. This fault is well exposed, is vertical, has a strike of N. 75°–80° E. and has a total vertical displacement of about 150 feet. The north block has been tilted, relatively, and may have undergone considerable horizontal movement. A minor northward dipping thrust fault occurs south of the vertical fault.

The fault surfaces of minor thrust planes observed by me north of Hollywood, as already mentioned, exhibit when examined closely definite grooves and scars which show that the upper, northern block moved southward over the under one, on planes dipping about 35°–40° N. This is what we would expect in view of the relative resistances, which are least upward and toward the depression.

The several types of faults noted by Hoots, the vertical strike-slip fault with horizontal or diagonal displacement, the vertical fault with vertical throw, and the overthrusts, constitute a complex which

differs materially from the large thrust structures, with almost exclusive dip-slip, described by Hill as characteristic of the San Gabriel Range. Nevertheless, the Santa Monica is a strongly uplifted block, and its general setting is homologous with that of the San Gabriel. Recalling the description by Noble of the vertical, strike-slip San Andreas fault together with the vertical displacements and thrusts associated with it, we find a close resemblance to the complex that affects the southern margin of Santa Monica heights. It seems reasonable to conclude that the evidence points to the action of similar stresses, similar in kind, though perhaps differing in relative intensity and effects.

The vertical faults with horizontal, or near-horizontal, strike-slip displacements appear to be shears developed by a force couple lying in a horizontal plane, the vertical displacements are attributable to wedging, which though inclined in the deeper sections is often vertical near the surface, and the thrusts are minor, but significant effects of compression. Compression is clearly indicated by the uplift of the Pliocene erosion surface, an uplift that is quite inconsistent with any assumption of horizontal tension.

Any description of the San Gabriel and Santa Monica ranges must recognize not only that they are homologous but that they are separate and in some respects unlike. Between them lie the San Fernando Valley, a depression deeply filled with sediments and alluvium, and the Verdugo mountain block, an upthrust mass of the basement complex. The basal overthrust of the San Gabriel Range, the Sierra Madre fault, after defining the southern side of the range, turns northwest between it and the Verdugo Mountains and passes the northeastern end of the Santa Monica Mountains at a distance of some 10 miles. If the basal overthrust be the dominant or controlling east-west feature, the structural relations of the two ranges must be regarded as distinctly individual. But there is reason to think otherwise.

A fault, known as the Foothills fault, is indicated at several points along the base of the mountains just above the all-obscuring alluvial fans and in small outliers. It appears to be a zone of vertical shears of slight vertical displacement, like the one described by Hoots as crossing Potrero Canyon near Santa Monica City and like those

shown in his section AA' east of Pasadena. Being close to the margin of the great depression covered by the plains, these faults may be regarded as minor elements of the profound displacement. If they truly represent the general effect of faulting, it is that of a vertical shear; not a single parting, but a complex zone involving displacements in horizontal as well as in vertical direction, as actually observed in the exposed sections. In his accompanying map, after Hoots and Kew, the Foothills fault zone, though not so named on the original, is shown as practically continuous. Accepting that continuity as a fact, we find the San Gabriel and Santa Monica ranges to be similar, though distinct, minor effects of pressure and underthrusting along the northern side of the larger structural feature, the profound tectonic depression along their southern bases.

Let us go to the eastern part of the Pasadena–San Bernardino basin, where the plain appears to abut against the San Bernardino Range, but in reality extends southeast past it, and consider that outstanding mountain mass.

SAN BERNARDINO RANGE

The structural geology is unfortunately not critically studied. The mountain mass stands practically surrounded by plains or low passes and has been considered in effect as a horst. In that case the faults which define it must be considered as high-angle upthrusts. They are more probably underthrusts, similar to those that underlie the San Gabriel Range.

We may cite the physiographic and topographic evidence of uplift, which can, of course, be interpreted either way.

Along its crest in the western portion the range is flat enough to carry a road at an elevation varying between 5,500 and 6,000 feet. This may be regarded as the elevation of the Pliocene matureland in that area. Farther southeast the altitudes are greater and there appear to be two topographic flats of different ages. The upper and older one is raised to an altitude of about 10,500 feet and carries the monadnocks of San Bernardino Peak (10,630 ft.) and of San Gorgonio Peak (11,485 ft). The lower is represented in passes and spurs between 6,000 and 7,500 feet but, being indicated by valley-widening rather than by broader planation, is not of uniform elevation. If,

as seems undoubtedly to be the fact, we correlate the lower surface with the Pliocene matureland, then the upper dates from late mid-

FIG. 2*a*.—San Jacinto Peak; looking southwest at the precipitous frontal, northeastern face.

FIG. 2*b*.—San Gorgonio Peak, San Bernardino Range; looking southeast at the broad summit, a peneplain remnant.

Tertiary time. It appears to be a unique survivor of a topographic surface that has elsewhere vanished or is unrecognizable. It may, perhaps, be correlated with the flat valley of Bear and Baldwin lakes,

which lies separated from it by a fault valley in the northern part of the range, at an altitude of 6,700 feet. Vaughn, however, who clearly identified the old surface between San Bernardino and San Gorgonio peaks,[7] sought to distinguish two cycles between the oldest and youngest, where the foregoing description would indicate but one and that of mature development only. However the slight difference of interpretation may eventually be decided, the occurrence of these old features at altitudes high above their natural levels is proof of notable uplift.

The faults that outline the mountain mass and its outliers are undoubtedly complex. They comprise vertical faults, which have been regarded by some as normal gravity faults, but which may be thrust faults curving up toward verticality as they approach the surface, i.e., ramps; or they may be vertical shears with strike-slip displacements. And associated with these are low-angle thrusts on which the basement complex is pushed over relatively very young gravels. Woodford and Harriss give some account of local structures of this character in the northern salient of the range,[8] and Noble[9] explicitly describes the effects of compression to which he attributes the uplift of the northwestern part of the range. We quote:

> Beyond a terrace rises a granite mountain known as Cleghorn Mountain, which is part of the extreme western end of the San Bernardino Range. Upon the sloping surface of the mountain lie remnants of the basal beds of the younger upper Miocene formation, the beds everywhere dipping parallel with the granite slopes upon which they lie. The slopes are therefore exhumed surfaces of erosion, and their attitude is an index of the mountain structure. The long slope by which Cleghorn Mountain descends westward to Cajon Creek is one of these surfaces and represents a downwarp of the west end of the San Bernardino Mountains to Cajon Pass. Cleghorn Mountain is an asymmetrical bulge or arch raised on the south along the Cleghorn fault and tilted westward to Cajon Pass and northward to the Mohave Desert. Its structure is typical of all the western part of the San Bernardino Mountain mass in view toward the east, essentially a succession of crustal blocks, each of which is tilted north and is raised on the south along a northward-dipping reverse fault.

[7] Francis Edward Vaughn, "Geology of the San Bernardino Mountains," *Univ. Calif. Dept. Geol. Sci. Bull.*, Vol. XIII (1922), pp. 319–411.

[8] A. O. Woodford and T. F. Harriss, "Geology of Blackhawk Canyon, San Bernardino Mountains," *Univ. Calif. Dept. Geol. Sci. Bull.*, Vol. XVII (1928), pp. 265–92.

[9] L. P. Noble, "Excursion to San Andreas Fault and Cajon Pass," *16th Internat. Geol. Congress Guidebook 15* (1933), pp. 10–11.

This is typical ramp structure. Noble continues:

> The mass as a whole was raised by compression. Inasmuch as it is composed of massive crystalline rocks, the deformation has resulted in reverse faults, shearing, arching, and tilting. If it had been composed of sedimentary rocks the same deformation would have resulted in folding and thrusting.

The thrust structure developed along the western front of the San Bernardino Range is characteristic of the lateral displacements accompanying the vertical shear which is the main San Andreas fault. The association of a vertical shear or system of parallel vertical shears, due to rotational stress of a force couple, with effects of compression across the sheared zone has been so well described by Noble in the passages quoted from his account of the San Andreas fault zone that further emphasis on this general relation seems unnecessary. The San Andreas fault extends not only past the western end of the San Bernardino Range but also along its southwestern side, beyond San Gorgonio Pass. There is independent evidence, to be described presently, of intense compression in the northern end of the San Jacinto Mountains, south of the pass. There can be no doubt of the compressed, thrust structure in the opposed base of the San Bernardino Range, even though it is so obscured by alluvium as to escape observation.

If, as is logical, we attribute the great elevation of the San Bernardino heights to compression, it follows that the stress must have affected the entire section, and thrusts should appear on the northern as well as along the southern side. Vaughn and also Woodford and Harriss in the articles already cited present evidence of thrusts on which granite overlies alluvium. They appear to be minor displacements in a salient. They indicate the action of the compressive stress in the expected direction. They may probably be minor shears rising from an underlying major sole.

Within the San Bernardino Range occur longitudinal faults of notable magnitude. The most pronounced is followed by the canyon of the Santa Ana River, which is cut in soft Tertiary (probably Pliocene sediments) between steep walls of granite. Vaughn characterized the structure with reason as a "graben," but he was in doubt as to the nature of the faulting, whether vertical normal faulting, according to the interpretation current fifteen years ago, or

some other type of displacement. In view of the demonstrated effects of compression and of the inference that the stress pervaded the mountain mass, it is probable that the Santa Ana "graben" is defined by two ramps, the one dipping northward, the other southward away from it. The dip of the ramps may be vertical near the outcrop, having the attitude of thrusts directed toward the surface because of slight resistance, but would flatten out in depth.

While the structure of the San Bernardino Range cannot be said to have been determined so definitely as has been that of the San Gabriel, it is apparent that it is characterized by effects of intense compression and the mass has been raised by underthrusting of a complex nature.

In order to follow the eastern margin of the San Andreas fault zone southeastward past the Salton Basin, it would be desirable to describe the structures of the Orocopia-Chuckwalla and Chocolate ranges. But the data are lacking. It seems probable that the orogenic effects may both resemble and differ from those described above. If, as is possible, the stresses affecting southwestern California have been directed in a north-south bearing the development of thrusts should be more pronounced in a range trending east-west, like the San Gabriel, than in one that strikes northwest-southeast, as the more southern heights do. On the other hand, vertical shears, striking parallel with the orogenic trend, should be dominant in the latter mountains. That there are effects of compression there is shown by the recent uplifts, but these are considerably less than those in the San Bernardino and San Gabriel and may thus indicate that the transverse compressive stresses have been weaker.

In the general outline of the structure of southwestern California we have already indicated the continuity of the tectonic depression which constitutes the margin of the area, within the San Andreas fault zone and the Foothills fault. It stretches from the Gulf of California to the Santa Barbara Channel. We shall, perhaps, be better prepared to interpret its buried structures if we first examine those that are exposed in the central mass, which takes in everything between the depression and the continental margin.

STRUCTURE OF THE CENTRAL MASS

The mountain region within the depressed margin of southwestern California is marked, at least in the northern and better-known section by three parallel fault zones, as already stated. They are the San Jacinto on the northeast, the Elsinore in the middle, and the San Pedro on the southwest. We may first consider the San Jacinto fault zone and the mountains of the same name.

San Jacinto Peak towers above San Gorgonio Pass from an altitude of 10,805 feet, thus vieing in elevation with the other Pillars of Hercules, San Bernardino and San Gorgonio peaks, north of the depression. As with them its summit is a monadnock, rising from a flat surface of erosion of an earlier cycle, but whether that cycle be pre-Pliocene or Pliocene appears not to be readily determinable. In any case the physiographic facts prove very great uplift since that not remote period of erosion.

The mountain mass as a whole is a bunch rather than a range, for its diameters, 16 by 25 miles, give it a somewhat rounded form. This is especially true of the higher portion, above 8,000 feet. It is completely surrounded by faults, by the San Jacinto shear along the southwestern side, the Palm Springs fault along the eastern side, and by a very complex system of conjugate faults which spreads out from the northeastern and northern sides.

The San Jacinto fault zone is a wide belt of intense fracturing, similar in general character and degree of deformation to the San Andreas fault zone in the section north of Cajon Pass as described by Noble in the passages already quoted. There is a main, vertical shear, the San Jacinto fault itself, which lies along or near the northeastern margin of a crushed belt that varies from 1 to 4 miles in width. The known length of the main fault is about 70 miles. At the northwest it first appears in low hills west of San Bernardino, rising, as it were, from the depths below the plain. An eroded scarp, descending steeply from the mountain, cuts off the spurs along its southwestern slope. About midway of its extent the scarp is set back about 2 miles and the fault zone widens accordingly. Toward the southern end of the known trace the scarp dies out and the fault is lost among low hills that are nearly buried in alluvium. Farther

south stretches a wide plain of gravel and sand. According to one view, the San Jacinto fault zone continues beneath the plain and may be regarded as the locus of the numerous earthquakes that are focused beneath the Imperial Valley. According to another interpretation, there is no continuous fault beneath the plain, but a sequence of shorter shears, offset en echelon. I, myself, held the former opinion until recently, but as a result of a reconnaissance of the region with special reference to jointing and faulting in the Peninsula Ranges I now think the second more probable. The facts and reasoning will be given in the sequel.

Palm Springs fault cuts along the eastern side of San Jacinto Mountain in a nearly straight line for some 20 miles. At its southern end it might be regarded as a right-hand branch of the San Jacinto zone, but it is of sufficient magnitude to be considered an independent fracture, in so far as any one shear may be independent of another in a complex system. At its northern end it passes beyond the mass of the mountain into the plain of Coachella Valley and is lost.

Palm Springs fault strikes about N. 10° W., and San Jacinto fault zone, N. 55° W. The two embrace an angle of 45°, the mathematical angle of shear. This may be interpreted as evidence that the Palm Springs is an effect of pressure normal to the San Jacinto; and there is no question but that a component of pressure normal to that plane has existed. That the two faults cut out the mountain block seems beyond doubt and that pressure against them would drive the wedge north about 30° west would follow as a mechanical result, if the pressure were competent. That there has been such a movement is indicated by the evidence of faulting at the northwest end of the mountain mass, at the stoss end.

For information regarding the structural details of the spurs of San Jacinto Mountain south of San Gorgonio Pass, I am indebted to the Metropolitan Water District of Los Angeles and particularly to Mr. L. H. Henderson, geologist. In locating and driving the Potrero tunnel of the Colorado River aqueduct, a condition of faulting much more complex than any that had been anticipated has been encountered. It has been accurately surveyed by Mr. Henderson, and, although he has not yet published any account of it and looks for-

ward to doing so when the work shall be completed, he has given permission to use the data in this discussion. Accordingly, the general plan of the structure is presented in Figure 3, as taken from his mapping. The area may be called the Potrero fault field.

Two sets of shears are apparent, the one trending northwesterly, parallel with the San Jacinto fault zone, the other diverging from it at angle somewhat under 90°. The angular relation is that of conjugate shears. The prevailing rock is essentially homogeneous granodiorite. The effects are those which pressure produces in a homogeneous brittle solid. We may infer that we have to interpret the fault system accordingly; i.e., it is the result of pressure acting upon the granodiorite, when the rock was solid and so near the surface that it was brittle, not plastic. The direction of pressure, obtained by bisecting the acute angle, is directed slightly west of north, east of south. Back of this inference lies the assumption that the active pressure was exerted from south toward north, from the side of the San Jacinto fault. That the assumption is justified is indicated by the spreading of the faults, which may be explained as follows.

Trending in a gentle curve toward the northeast, the shears that belong to that set diverge until the angle which they make with the San Jacinto set increases from about 80°–105° or more. The angle changes from acute to obtuse. We may not attribute this to a change in the condition of the rock, since the environment remains the same, and the solid, if brittle in one part, must have been brittle all through. An alternative explanation is suggested by comparing the spreading faults with the lines of stress induced in a solid under pressure. The lines of equal stress diverge in a similar manner and would direct the shear as the unit stress rose in intensity to the point where it exceeded the shearing strength. But this divergence spreads as the distance from the active source of pressure increases, i.e., from south to north in this case.

It will be noted that the northwest-striking faults dip northeastward. If the pressure was from the south, they are underthrusts. The angle of dip is steep, generally above 60°, and approaches vertical or is actually vertical in the San Jacinto zone. Hence it seems more than likely that the San Jacinto resembles the San Andreas

fault in that it consists primarily of a deep-going vertical shear, but is combined with a thrust in such manner as to curve in under the mountain mass in the form of a ramp. The uplift which is expressed in the bold scarp, 2,000 feet high, would result from displacement on such a ramp fault. It may be remarked in passing that uplift follows when one mass is thrust under another, much as it does if one is pushed over.

In the course of tunneling, the nature of movements on the above-described fault system has been observed by Henderson with an understanding not possible on surface evidence alone. The fault zones are usually from one to several hundred feet wide, and the fragments of rock of all sizes between the walls are rotated past one another. Angular openings are numerous. In some cases the rotation has gone so far, however, that the fragments are rounded and even have the appearance of stream boulders in sand. It is obvious that the displacements have been notable and have occurred under very moderate load, allowing the broken mass to shift within itself between the walls.

The faulted area which has thus been studied in detail underlies a rugged foothill region northwest of San Jacinto Mountain. The foothills vary from 2,500 feet to 4,000 feet in altitude above sea. The mountain proper carries summit levels near 8,000 feet. The difference is stepped up in a bold scarp that faces northwest, parallel with the northeast-trending fault system. There is little doubt but that it is a fault scarp and the fault would necessarily be an upthrust fault, a ramp rising from under the main mass. The internal structure has, however, not been worked out.

There is still much to learn about San Jacinto Mountain, but Henderson's work, taken together with the general structure of the region, demonstrates that it is a closely sheared mass, cleft between the San Jacinto, Palm Springs, and San Andreas faults. It follows also that the one direction of active pressure which suffices to explain the complex shearing is directed from south by east toward north by west.

North of the faulted area described the San Gorgonio Pass stretches from east to west, the highest section of the marginal depression. Beyond the pass stands the San Bernardino Range.

Whether we regard the latter as a passively resisting block or as a mass that is being pushed southward (and theory is here fancy free), the position of the zone of the pass is that of a strip in a vise. It is squeezed between the mountain masses and is relatively high, as compared with the sections of the depression northwest and southeast of it, because it has been squeezed.

The San Jacinto fault zone extends northwest beyond the area just discussed and approaches the San Andreas. As hitherto mapped it is shown as joining the latter north of San Bernardino. Such may be the fact, but the alternative suggestion that it ends in the crushed and depressed area west of San Bernardino before reaching either the San Andreas or the Foothills fault seems equally probable. The rotational displacements in an anti-clockwise direction, which characterize the movements along it, would tend to twist it westward.

The southward extension of the San Jacinto fault zone beyond its junction with the Palm Springs fault is uncertain and will be discussed under the heading "Peninsula Ranges." We pass to consider the Elsinore fault.

Some 20 miles southwest of the San Jacinto fault, opposite the intensely displaced section just described, ranges the parallel and most concentrated part of the Elsinore fault. It appears to be a straight shear, striking N. 50° W. for a distance of 50 miles along the northeastern base of the Elsinore Range. A broad, alluviated valley, which includes the shallow basin of Elsinore Lake, indicates, presumably, a zone of intersecting fractures, and certainly represents a depressed segment.

The Elsinore Range lifts its crest to 3,000 feet above sea, with peaks that reach 4,500 feet, and presents a bold, steep face toward northeast. Its southwestern slope is a long, gentle incline, between 20 and 30 miles wide, a tilted peneplain descending to the coast. It is, in effect, a small replica of the Sierra Nevada and may be regarded as a tilted block, bounded along its northeastern side by a sequence of stepfaults, on each of which the displacement has been a dip-slip upthrust.

At its southern end the 50-mile stretch of the fault terminates in El Rincon, a pocket-like valley, and in the line of shear rises a broad, smooth mountain summit, a solid mass of granodiorite. In it and

around it the shear appears to feather out. We shall consider the suggestions of offsetting in connection with the account of "Peninsula Ranges" farther on.

At its northern end the main section of the Elsinore fault divides into three principal branches. One diverges toward the right and, trending N. 35° W., is lost in the deep basin south of the San Gabriel Range. A second holds straight on, in the line of the main fault, and presently fades out. The third and dominant branch turns westward, to N. 65° W. It is known as the Puente Hills or Whittier fault and extends toward Los Angeles until it too is lost in the deep basin.

It is worthy of special note that movements on the Puente Hills branch are dominantly in the strike-slip direction, as is demonstrated by the minor but oil-producing folds, the Santa Fe Springs, Coyote, and related domes, which are effects of the shortening on the north-south diagonal of the stress rhomb, in consequence of rotation and strike-slipping along the northwesterly trending major fault.[10] The movement is anti-clockwise, the southwestern segment moving northwestward relatively past the northeastern one. It is, practically without question, characteristic of the main Elsinore fault as well as of the Puente Hills branch, and, since the tilting of the Elsinore indicates dip-slip movement also, we find here another example of the association of the vertical shear with an upthrust displacement on a ramp.

Comparing the Elsinore fault with the San Jacinto fault zone, it appears to be less intimately crushed, simpler and shorter, and bent more obviously toward the west at its northern end. The stresses that have produced the San Jacinto seem to have been greater, the dynamic effects more nearly comparable with those exhibited by the San Andreas fault zone.

We may next consider the apparently still slighter San Pedro fault zone, which lies some 25–30 miles southwest of the Elsinore, striking N. 40° W.

The San Pedro fault zone does not appear at the surface in any strongly developed fault. It is best known as the locus of the foci of

[10] R. N. Ferguson and C. G. Willis, "Dynamics of Oil-Field Structure in Southern California," *Amer. Assoc. Petr. Geol. Bull.*, Vol. VIII (1924), pp. 576–83.

the Inglewood (1920) and Long Beach (1933) earthquakes, situated, of course, some miles below the surface. As thus indicated it is a vertical shear in the basement complex, subject to strike-slip displacement in an anti-clockwise direction. The deep-seated movements affect the overlying sediments, producing slight shearing parallel to the main fault, tension fissures across the direction of elongation, and compression across the shortened diagonal. The effects are seen in the complex structures discovered in drilling for petroleum and in the productive oil-bearing domes of Signal Hill, Dominguez Hill, and the Baldwin Hills.

At its northern end the San Pedro fault zone ends under the depression south of the Santa Monica Range. The southern end is under the ocean and cannot be traced, even by earthquake foci. The southern-most point that is definitely recognizable is the focus of the Long Beach shock, which was situated about a mile offshore, at a depth of about 10 miles. The severity of the earthquake of 1812 at San Juan Capistrano may indicate that the active fault extends 20 miles or more farther southeast. It is doubtful that it continues far beyond this limit.

In the western margin of the San Pedro fault zone stands the well-known height of San Pedro or Palos Verdes Hills. It is a block of older rocks, Cretaceous and earlier, surrounded by Tertiary, with fault contacts. It exhibits upon its slopes a succession of marine terraces that mark the stages of recent uplift. It is clearly an upthrust block, raised by compression and by analogy regarded as underthrust on inclined planes which converge under it.

The active earthquake shear, the superficial folds and thrusts, and the upthrust of the Palos Verde block demonstrate the action of pressure on the San Pedro fault zone and prove that it is a consistent feature of the general system to which the Elsinore, San Jacinto, and San Andreas fault zones belong.

One more member of this series remains to be mentioned, the fault that defines the northeastern side of San Clemente Island. It lies about 55 miles southwest of the San Pedro zone, trending about N. 40° W., and may be said to have a known length of about 30 miles. While the straight northeast coastline of the island would suggest its presence, definite proof of its existence is provided by the

occurrence of earthquake activity determined by the Seismological Laboratory at Pasadena as being developed on it.

We have described the structure of the northern part of the central mass of southwestern California and may sum up the facts by stating that it is characterized by three major shears, which are known as the San Jacinto, Elsinore, and San Pedro faults, and which are associated with a variety of minor faults that are predominately to be classed as thrusts of one type or another. This major shearing is strongly developed in the northern half of the area north of the Mexican border. It is not so obvious in the southern half; indeed it seems quite possible that the three great fault zones feather out southward and are represented by shorter, less continuous shears, offset en echelon. We pass to the consideration of the southern area.

PENINSULA RANGES

The mountain region that goes by this name is an elevated, warped plateau. Its general landscape is that of the Pliocene mature-land, which is characterized by wide valleys surrounded by hills, mountains, and even mountain groups. Under the Pliocene climate the granitic rocks decayed deeply, and large boulders were isolated in great numbers. The removal of soil has exposed them on the peaks and slopes, the former now being often nothing more than boulder piles. Larger residual boulders also stand out in the valley flats, their aged surfaces often showing a typical weathered, bread-crust character. Being elevated above its level of erosion, the old landscape is being vigorously attacked and is penetrated by youthful canyons.

This well-developed physiographic record is now complicated by warping and faulting, the natural effects of unequal elevation. There are valleys whose basin-like form and large diameters suggest tectonic depressions, yet their expanse is not incommensurate with tributary valleys, sloping gently toward them. The basin known as Valle de San Jose in the Ramona quadrangle is a case in point. With a valley floor raised to 2,800 feet above sea, it lies among mountains that attain 4,500 feet and locally more. Long spurs descend into it, without marked breaks, and the headwaters of San Luis Rey River unite in it from widened valleys of erosion. It presents the appear-

ance of an intermontane amphitheater, due to erosion of softer rocks among the harder masses. The rocks are schists versus massive granodiorite.

On the other hand, the differences of elevation are considerable, and the Pliocene matureland can be identified in valley floor and mountain summit. General uplift of the whole mountainous plateau is clearly evident in the rejuvenation of the streams, and unequal local uplift is equally obvious. The deformation may have found expression in either one of three ways, namely: (1) by warping without fracture, (2) by warping accompanied by stepfaulting on planes of schistosity or jointing, and (3) by high-angle, upthrust faulting. Any tilted slopes or scarps thus produced have certainly been attacked by older and by consequent drainage lines and are more or less dissected.

The region has been studied by Fairbanks, by Sauer, and by Miller,[11] and decided differences of interpretation have resulted. The two earlier writers incline toward the physiographic interpretation, whereas Miller emphasizes faulting. In a recent reconnaissance, during which I viewed the landscape from seacoast to Salton Basin and southward across the border into Mexico, I failed to find evidence of extensive faulting and was led to think erosion and warping were chiefly responsible for the scenic character of the mountains. The degree of credit to be assigned to either agency could not, however, be determined even locally without much more thorough investigation, including mapping of formations.

The object of my reconnaissance was to ascertain what, if any, evidence might be found of the continuation of the three major faults of the northern area, where they are indicated, more or less doubtfully upon the fault map of California.[12] I had thought the doubtful traces too conservative and expected to find the fault zones extending to the Mexican boundary and beyond. My expectation

[11] H. W. Fairbanks, "Geology of San Diego County," *Calif. Min. Bur. 11th Ann. Rept.* (1893), pp. 76–92; C. O. Sauer, "Landforms in the Peninsula Range," *Univ. Calif. Dept. Geol. Sci. Bull.*, Vol. III (1929), pp. 199–290; W. J. Miller, "Geomorphology of the Southern Peninsula Range," *Bull. Geol. Soc. Amer.*, Vol. XLVI (1935), pp. 1535–62.

[12] *Fault Map of California*, compiled by Bailey Willis and H. O. Wood, with the aid of many contributors. *Southern California* by Wood and others. (Washington, D.C.: Seismological Society of America, 1922.)

was disappointed. I did not find continuous faults, although relatively minor shears are presumably present.

The criterion which I sought to apply was the occurrence or non-occurrence of the collateral structures, which are so strongly developed in the northern area. In addition to physiographic evidence, such as the displacement of the Pliocene erosion surface, I looked for appropriate conjugate jointing.

In homogeneous granodiorite one finds along the margins of the great shear zones joints that are oriented parallel and normal to the main shears. They occur along the Elsinore and San Jacinto fault zones to a distance of a mile or two from the principal fault. It seemed probable that in the Peninsula Ranges strains of this kind might betray the presence of the main shear, even though strike-slip displacements had failed to produce conspicuous differences of elevation and scarps.

Subsidiary joints of this character, representing effects of strain in the homogeneous wall rocks adjacent to the main zone, should strike in this region from N. 45° to N. 50° W. and from N. 40° to 45° E. I found the almost universal orientation of the very widespread and intimate jointing to be about N. 15° W. and N. 75° E. with variations of 10° one way or the other. It was a primary jointing imposed upon the granodiorite during or soon after cooling and was related to the hydrostatic pressures, normal to the north-south walls bounding the intrusion, as shown by schlieren and other flow structures. Shearing, if any, had been controlled by the direction of schistosity. Where the granodiorites exhibit homogeneity, without parallel arrangement of minerals, as is commonly the case, there is no evidence of lateral slipping.

While the nearly north-south, east-west orientation of the jointing was almost universal in occurrence, there were exceptions. The subsidiary jointing, northeast-southwest and northwest-southeast roughly, was found along the Elsinore fault north of El Rincon, along the stretch where there is no doubt of the existence of the main shear. It was found on both sides of El Rincon itself, where the line of the Elsinore runs directly into a flat-topped mountain of unbroken granodiorite. It is evident that the main shear ends, but the fault map shows a continuation along a parallel line a little

offset to the east. The supposed continuation follows the canyon of the San Luis Rey River, which is eroded along the strike of a band of schist. Granodiorite outcrops occurring locally within the canyon exhibit the general, but not the subsidiary, jointing. It would appear that the Elsinore fault actually ends by dispersing into several branches around the terminal mass of granodiorite.

However, at the head of the canyon of San Luis Rey, 10 miles east of El Rincon and thus offset from the line of the Elsinore fault, there is a steep mountain front facing the wide amphitheater of San Jose del Valle. It may be interpreted as an effect of erosion on steeply dipping schist, the local rock, or as a slightly retreated fault scarp. The latter interpretation is indicated as the correct one by the displacement of the Pliocene surface, which floors the Valle and caps the mountains, 1,500 feet above it, and also by the location of slight earthquake tremors in this vicinity. The latter are determined by the Seismological Laboratory at Pasadena, with an uncertainty of position of a few kilometers.

The length of this scarp is 5 or 6 miles. While recognizing that it represents a fault, I regard it as a very local displacement along a nearly vertical strip of schist, which has also served to determine the courses of the streams that line up along it. I could not observe similar evidence of faulting around the other sides of the relatively depressed Valle. The long mountain spurs that lead down into it carry the warped Pliocene surface in remnants that represent its warped form, and the broad canyons or valleys that lead into it are logically eroded in the tilted slopes.

Reconnoitering along the strike of the supposedly continuous Elsinore fault, I observed adjusted streams, whose canyons might suggest faulting, but no other evidence of it until I reached the escarpment east of Jacumba, 50 miles southeast of the faultlet just described. There the plateau of the Peninsula Ranges fronts upon the great depression of Salton Sea and Imperial Valley with a difference of elevation amounting to 3,000 or 4,000 feet. The escarpment is a wide fault zone where it descends through what is called Boulder Park to Coyote Wells. Not only is it of great height and very steep, but the granitic rocks exhibit both sets of jointing, that which I consider primary (north-south and east-west) but also that

which I regard as an effect of local strain (northeast-southwest and northwest-southeast).

Trending about N. 35° W., the plateau front becomes extended in spurs that presumably indicate that a flexure replaces the upthrust fault, as is so commonly the case in general. Toward the southeast the bold face extends across the Mexican line and is the occasion of the Cantu Grade on the highway that follows south of the boundary. The grade, however, descends one side of a deep, precipitous canyon, on the eastern side of which the mountains rise to the same height as on the western. The schists and intrusives of the canyon wall, though greatly disturbed, fail to show the subsidiary jointing, and it appears that the fault, so obvious 10 miles to the northwest, is here but slightly developed, if at all. The escarpment and presumably the displacement are offset a few miles to the east, where the mountain front overlooks the Laguna Salada of the Mexican desert plain.

Pursuing this question of the extension of major faults southeastward we may consider the San Jacinto fault zone. It is clearly traced to its junction with the Palm Springs fault and for some 10 or 15 miles farther along its strike. The mountain ranges that define it then sink beneath the plain of the Borego Desert, and surface evidence of the shear zone disappears. El Centro, where earthquake shocks frequently occur, is situated on the strike, at a distance of about 60 miles, and near midway of that stretch stands Superstition Mountain, which may be either an upthrust fault block or a nearly buried monadnock. No one will doubt the probability of faulting in the profound depression of the Salton Basin, in the southwestern margin of which this zone lies, but whether it be a continuous shear or a sequence of local displacements, offset en echelon, remains indeterminate. Faulting in the central section of the basin, 12 miles northeast of the San Jacinto strike, and therefore quite off of it, is indicated by the very common occurrence of earthquake shocks reported from Brawley.

I have dwelt at some length upon the results of my effort to trace the major, primary shear zones of northern southwest California into the southern part of that area because I failed to find what I expected and was obliged to modify the hypotheses I had entertained very materially. We may now endeavor to interpret the group of

structures described above and to elucidate the problem of the origin of stresses.

HYPOTHETICAL ALTERNATIVES

The group of structures, shears and thrusts of various types, accompanied by folds in appropriately bedded rocks, presents a problem in movement and stresses causing movement for which we have, as yet, only speculative explanations. Southwestern California is not unusual in being a riddle in that respect, but the facts do suggest solutions somewhat more clearly than is commonly the case. We may consider a sequence of suggestions which spring from past experience or from more recently developed ideas.

Hypothesis I.—Let it be assumed that there long has been and still exists a pressure against the continental margin of southern California which originates in a sub-Pacific segment of the earth's crust. Limit the action to that of a direct linear stress, pushing in a direction normal to the coast, a nonrotational stress.

This hypothesis is in line with the inferences drawn from Appalachian structures and demonstrated to be correct for that region by the studies of R. T. Chamberlin.[13] It is a commonly accepted idea, which I myself have long regarded as fitting for general application. But it does not agree with the facts of structure as I have observed them in central California, and I do not find any stronger evidence in its favor in southern California. The dominant structures, the major shears, are quite inconsistent in strike and dip with the expectable effects of direct, normal pressure.

Hypothesis II.—Let it be assumed that the source of the stress has been sub-Pacific, as in Hypothesis I, and also that it has been a simple nonrotational pressure, but that the direction of it has been approximately at 45° to that of the major shears (i.e., about N.–S.) in accordance with mechanical principles.

This hypothesis would be consistent with the orientation of the major shears, but, since the direction of the force was assumed to cause them, that agreement proves nothing. The E.–W. strike of the great thrust under the San Gabriel and Santa Monica moun-

[13] R. T. Chamberlin, "Strain Ellipsoid and Appalachian Structures," *Jour. Geol.*, Vol. XXXVI (1928), pp. 85–90.

tains, which has raised them and caused the depression of the Los Angeles–San Bernardino trough, is supporting evidence of a N.–S. directed pressure, but it does not indicate the origin. And, when we examine the jointing in the extensive exposures of the granodiorites, we fail to find that general agreement with the strike of the major shears which we would expect, if such a pressure had been applied to the entire body. The almost universal N.–S., E.–W. jointing may be older, as suggested in an earlier paragraph, but it cannot be due to a N.–S., nonrotational pressure.

Hypothesis III.—If, nevertheless, we regard the evidence of the action of a N.–S. pressure as valid, as it seems to be, we may modify Hypothesis II by assuming that the stress has had a rotational effect. An adequate nonrotational stress, properly oriented, would cause the primary shears, the San Pedro, Elsinore, San Jacinto, and San Andreas, while a rotational effect would produce the strike-slip displacements. We would expect, however, that shears which were due to a general pressure would extend right through the granodiorite masses, which they do not do; and, if there were any inequality of development, we would anticipate that the one nearest the application of the pressure would show the maximum effect; i.e., the San Pedro should be the longest and should be accompanied by the more intense crushing. The opposite is the fact; the San Andreas and San Jacinto are far more strongly developed in every respect.

Hypothesis IV.—In the preceding suggestions it has been assumed that the primary effect of pressure upon the mass of southwestern California was to produce the four major shears. Let it be assumed that that effect was secondary, the principal movement having in that case been a general rotation of the entire block, whose eastern boundary is the San Andreas fault, in an anti-clockwise direction. The rotating body would then have the action of a cam and would be subject to deformation as it pressed against the resisting frame formed by the pre-Cambrian nucleus, the San Bernardino block, and the San Gabriel and Santa Monica blocks. The intensity of the reaction would be distributed according to the displacement of the rotating body and the relative immobility of the resistance. It would be greatest along the San Andreas, as it is, similar on the San Jacinto, as it is, and less on the other two shears.

This hypothesis satisfies a large body of facts, but it leaves us without an adequate source for the rotating stress. Are we to seek that dynamic condition under the Pacific, or in the mass of southwestern California, or in the extension of the latter in the peninsula of Lower California?

Hypothesis V.—A north-south pressure being regarded as that which is demonstrated by the major shears and the thrust along the northern side of the area under discussion, it is possible, but not probable, that the source of the stress was sub-Pacific. The alternative that its origin is to be sought in the body of Lower California, including the section north of the political boundary, may well be considered. Let us suppose that that entire mass has been and is moving northward, either drifting or pushed by the ocean bed. Then its northern end, meeting with resisting bodies, would be the stoss end and would suffer deformation. It might be underthrust, as it is under the San Gabriel and Santa Monica blocks; it would be rotated and crushed against the San Bernardino block; and major shears would extend into its mass, starting from the northern side and progressing to greater or less distance southward, as they do. The hypothesis satisfies the facts, but it lacks motive power. It seems to be a good guess, but it remains no more than a plausible guess unless some reason can be found to explain the assumed movement of the great mass of Lower California.

Hypothesis VI.—Let us modify the postulate of Hypothesis V by substituting for the mass movement an elongation of the long narrow body of Lower California. The southern end might in that change push southward or remain stationary. The opposite end would push northward or remain stationary. The deformation proves that it pushed as if by elongation, but what cause or process can be suggested to account for that increase of length?

Consider the dynamic conditions in which the batholith of Lower California originated. Its mass was intruded into the outer shell in a molten state and cooled to solidification in its upper part. The more deeply buried magma remained molten for a long time, possibly down to the present. Cooling by conduction would be very slow indeed, even in terms of geologic periods, and it would presumably be retarded by radioactive heating. The effect of the prolonged

maintenance of high temperature upon the solidifying and solidified granodiorite would be to induce original or metamorphic gneissic structure, with the longer axes of the crystals oriented in a horizontal plane. The crystalline elongations would sum up centrifugally, and their total in any direction would be a function of the radius. They would either push out the frame of adjoining masses or the crust of the batholith would itself be sheared and forced up. The latter effect is found in the elevation and block-faulting that characterizes the peninsula: the displacement of the frame is to be seen in the structures east of the San Andreas fault and around the northern end, as described. The reaction upon the elongating body may be identified in the four major shears and minor fractures in the massive rocks and also in the folding of the sedimentaries.

Like Hypothesis V, Hypothesis VI satisfies all the known facts of the structure of southwestern California, and it has the advantage of being a direct descendant from the dynamic conditions that existed and probably still exist in the batholith of Lower California. That intrusion is, so far as has been determined, of Upper Cretaceous or possibly younger age.[14] It is a fact of general occurrence and of significant interest that the late Mesozoic and younger intrusions of the circum-Pacific islands and lands are very commonly associated with orogenic structures, such as strike-slip shears, block-faulting, folding, and thrusts. The widespread occurrence of this relation points to a dynamic connection and gives to the hypothesis of metamorphic orogeny very definite support.

Hypothesis VII.—The preceding hypotheses present themselves as more or less well-accredited explanations of the structure of southwestern California, and they constitute the available group in the present state of our knowledge. But there are residual facts which are emerging through the surveys of Levi P. Noble and others in the region north and northeast of the San Bernardino Range, in the southern portion of the Great Basin area. The structures are extraordinarily complex and intensely compressed. They demonstrate the very recent action of orogenic forces which cannot be attributed to, nor even related to, those which have deformed southwestern Cali-

[14] Woodford and Harriss, "Geologic Reconnaissance across the Sierra San Pedro Martir, Baja California," *Bull. Geol. Soc. Amer.*, Vol. XLIX (1938), pp. 1297–1336.

fornia. There is, therefore, reason to supplement Hypothesis VI by recognizing that the resistance met by the northward pressure was probably not simply passive. It also was active and opposed. Thus the tectonic depression that extends from the Gulf of California to the Los Angeles trough and the mountain ranges north of it lies in a vise.

REFLECTIONS

The momentum acquired in framing hypotheses may carry one too far toward conviction of the verity of what are perhaps nothing more than plausible inferences. Hypotheses VI and VII may be more persuasive than true. It is well for the writer to remember that Hypothesis VI is an application of his theory of metamorphic orogeny[15] and may be suspected of an influence of subjective reasoning. If it contains the germ of truth, it will survive the winter of doubt. It is well, therefore, that it should take its place with all the others of the group from I to VII and be held subject to the test of better and fuller knowledge of the facts in this and similar regions.

CONCLUSION

In concluding this study of the San Andreas Rift, which includes the previous article on the rift in central California, we may point out certain results that appear to be sustained by the facts. It seems that:

1. The rift is a mechanical effect, a strike-slip shear.

2. The mechanical effect is a result of the action of a stress which is directed from south toward north in the masses southwest of the parting.

3. The locus of the shear lies along the northeastern margin of the batholith of Lower California in the south and along the similar margin of the batholith of Salinia in central California.[16]

4. Northeast and north of the rift lie the rigid masses of the pre-Cambrian positive element of southeastern California, the batholiths of the San Bernardino, San Gabriel, and Sierra Nevada mountains, and possibly others not so well exposed. The rift follows a

[15] B. Willis, "Metamorphic Orogeny," *Bull Geol. Soc. Amer.*, Vol. XL (1929), pp. 557–90.

[16] R. D. Reed and J. S. Hollister, *Structural Evolution of Southern California* (Tulsa: Amer. Ass. Petr. Geol., 1936), pp. 84–85.

somewhat sinuous line between them and appears to have developed in the zone where their opposed bodies acted like the jaws of a vise.

5. The shearing stress may have originated beneath the Pacific Ocean or in the batholiths themselves. The latter inference has the advantage over other speculations in that it is a direct deduction from the dynamic activity of the batholiths themselves.

6. There is evidence, which is now being assembled by researches in the Mohave and Death Valley regions, that they have been the scene of very recent, as well as of earlier orogenic activity and a fuller understanding may probably lead to the recognition of pressures exerted upon the Sierra Nevada and other bodies northeast of the San Andreas to accentuate the deformation of the zone between the opposed stresses.

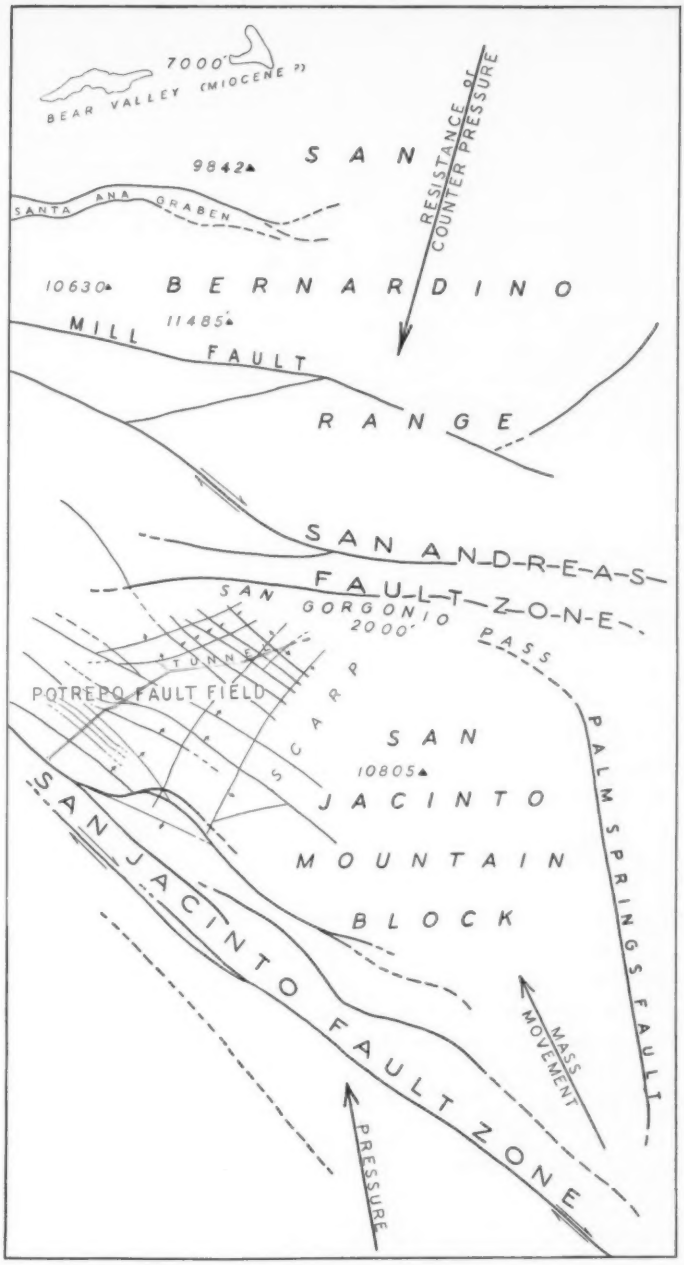

FIG. 3.—Fault systems of the San Jacinto and San Bernardino mountains and of the Potrero fault-field. (After Henderson.)

HYDROTHERMAL ALTERATION IN THE ROCKS OF PIGEON POINT, MINNESOTA

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ABSTRACT

Evidence is presented to show that two fundamental rock types, (*a*) diabase and (*b*) granite, are present on Pigeon Point and that so-called "intermediate" rocks associated with them are not true transitional products of magmatic differentiation but are diabases metamorphosed by thermal solutions after complete solidification. Other rocks of unusual appearance are sediments of the Rove formation contact metamorphosed by the granite and later hydrothermally metamorphosed.

INTRODUCTION

Many geologists both from the United States and from Canada have had occasion to visit Pigeon Point, Minnesota, and vicinity and to study its rocks. This is partly because it lies within the belt of International Boundary Surveys, but mainly because its rocks showed features difficult of explanation and hence intriguing to the investigative mind.

The writer visited the area in August, 1936, incidental to certain broad studies in mineralization. The following observations, relating mainly to the alterations which the igneous rocks and sediments have undergone since their original emplacement, are reported because they seem to afford an explanation of some of the features of the region that have appeared unusual and puzzling. Although the literature on Pigeon Point is voluminous, the reports by Bayley,[1] Daly,[2] and Grout and Schwartz[3] are of major importance.

The principal obstacle to a clear understanding of the rocks of Pigeon Point is the presence, in addition to diabases (by some termed "gabbros") and granites (the "red rock" of some writers), of certain

[1] W. S. Bayley, "The Eruptive and Sedimentary Rocks on Pigeon Point, Minnesota, and Their Contact Phenomena," *U.S. Geol. Surv. Bull. 109* (1893), 118 pp.

[2] R. A. Daly, "The Geology of Pigeon Point, Minnesota," *Amer. Jour. Sci.*, Vol. XLIII (1917), pp. 423–48.

[3] F. F. Grout and G. M. Schwartz, "The Geology of the Rove Formation and Associated Intrusives in Northeastern Minnesota," *Minn. Geol. Surv. Bull. 24* (1933), 103 pp.

rocks termed "intermediate," that in places seem to grade into diabase or granite or into the sediments of the pre-Cambrian Rove formation. These "intermediate" rocks are usually pinkish or mottled pink and greenish-gray. To explain them Bayley appealed to assimilation of sediments by the magmas, and Daly conjoined assimilation and magmatic differentiation. The present paper offers an alternative hypothesis of thermal alterations acting on rocks already completely solidified.

The diabases, the granites, and the sediments of the Rove formation will be considered in turn, their least altered representatives first being described and then the more altered types. The genetic significance of the alterations will then be discussed.

LEAST ALTERED DIABASES

LOCALITIES

Two olivine diabases studied came respectively from close to the International Boundary Survey monument near the tip of Pigeon Point and from a cliff on the north shore about one-third of a mile west of the tip. Two granophyric diabases without olivine were collected from points $2\frac{1}{2}$ and $2\frac{3}{4}$ miles west of the tip of Pigeon Point.

MEGASCOPIC CHARACTERS

The feldspars are white to light gray, and the ferromagnesian minerals dark gray to nearly black. The net effect is to give the rock a dark gray to nearly black tone. The largest feldspar or ferromagnesian prisms usually do not exceed 5–10 mm. in length. Prismatic forms are often as conspicuous in the ferromagnesian minerals as in the feldspars.

Olivine diabase from near the monument at the tip of Pigeon Point shows a typically ophitic texture with plagioclase in excess of augite. Dominant primary minerals in order of abundance are labradorite (near $Ab_{40}An_{60}$), augite, and olivine, the latter two interstitial with respect to the labradorite. Accessory primary minerals are apatite and magnetite. Small amounts of graphic intergrowth of quartz and orthoclase are interstitial and represent the last minerals to crystallize. Olivine diabase from one-third of a mile farther west along the north shore of the Point was nearly identical with that just described.

A typical example of granophyric diabase free from olivine was collected from near the crest of Pigeon Point ridge about $1\frac{1}{4}$ miles east of the mouth of Pigeon River. Its texture is ophitic and except for olivine it carries the same minerals as the specimen just described. In the interspaces, however, between the labradorite and the augite crystals, graphic intergrowths of quartz and orthoclase are abundantly developed. In a few places quartz alone occupies such interspaces (Pl. I *A*).

In a few places, as one-fourth of a mile west of the southeast tip of Pigeon Point, the diabase carries occasional phenocrysts of labradorite 2–4 inches across. Grout and Schwartz[4] observed gradations from such porphyritic facies into anorthositic gabbro.

THE MORE ALTERED DIABASES

LOCALITIES

Seven specimens of the altered diabases were studied under the microscope. Two of these were from the south shore of Pigeon Point one-fourth of a mile west of its tip. Four were from near the crest of the ridge 1–$1\frac{1}{4}$ miles west of Little Portage Bay. One specimen from the petrographic collections of the University of Chicago came from near the eastern end of the point.

MEGASCOPIC CHARACTERS

Most of these rocks are similar in texture and in coarseness to the little altered diabases already described, though some exceptions are noted below. In most of them, however, the feldspars are pink instead of gray and the color contrast between the pink feldspar and the gray ferromagnesian minerals gives the rocks a somewhat blotched appearance without, however, any regularity in the outlines of the pink or gray areas. Some of the altered diabases are indistinguishable without the aid of the microscope from some of the darker granites, but none shows the bright brick-red tone common in many of the granites, both fresh and altered.

MICROSCOPIC CHARACTERS

The beginnings of alteration in the diabases involve the development of scattered minute flakes of white mica in the labradorite.

[4] *Ibid.*, p. 47.

At the same time augite and diallage usually show partial alteration to hornblende or directly to chlorite with minor amounts of carbonate and epidote. Biotite alters to chlorite or rarely to an association of white mica and minute grains of magnetite. As chloritization of the pyroxenes and biotite becomes complete, the labradorite becomes more heavily flecked with white mica. Even in phases of the diabase that are only slightly altered, the orthoclase of the micrographic intergrowths is pink (from finely divided hematite) (cf. Pl. I *B* and *C*).

Up to this stage of alteration the secondary minerals have in general developed within the primary minerals and not across their boundaries, and as a consequence the original ophitic texture is perfectly preserved. A departure from the usual course of early alteration outlined above should be noted. On the south shore of Pigeon Point about one-fourth of a mile west of its southeastern tip the augite of diabase is replaced by a feltlike aggregate that appears to be antigorite,[5] without, however, destroying the ophitic texture. Hornblende is, in places, an intermediate product in the alteration to antigorite. In the hand specimen, the parts of the rock where augite has been replaced by antigorite have the general appearance of a greenish-gray chert.

The diabase from this locality is also peculiar in carrying in places plagioclase phenocrysts up to 2 inches or even 4 inches in length. Along the main contact between diabase and granite at this shore locality, the mutual age relations are not clear. There is a transition zone 1–2 feet wide along which with the unaided eye undoubted granite cannot be certainly distinguished from altered diabase. Under the microscope, however, granite and diabase in this zone can be clearly distinguished both by texture and by composition; there is no transition from one to the other, but both have been notably altered hydrothermally. Close to this locality small granite dikes up to 1 inch wide were noted in the diabase. These relations agree with Grout's observations: "If the granite is all of the same age it seems to be the latest igneous rock of the (Pigeon Point)

[5] The minute prismatic crystals of this intergrowth have parallel extinction, an index of refraction greater than balsam, and show gray as their usual and yellow of the first order as their maximum interference colors. Crystals are length-slow.

sill, for it cuts gabbro (diabase), anorthosite, intermediate rock and the roof and floor of the sill."[6]

Other diabases show more advanced stages of alteration which tend to obscure the original ophitic texture. Near the crest of Pigeon Point ridge about $1\frac{1}{4}$ miles east of the mouth of Pigeon River, one of the freshest of the diabases grades into a mottled pink and green facies in which augite and diallage show local alteration via horn-

TABLE 1

GENERALIZED SEQUENCE OF MINERAL CHANGES IN HYDROTHERMAL ALTERATION OF PIGEON POINT GRANOPHYRE DIABASES

Theoretically unaltered granophyre diabases	Least altered granophyre diabases	More altered granophyre diabases
Labradorite	Labradorite ↘ Fine white mica	Labradorite and white mica ↘ Albite
Orthoclase, Quartz } .....graphic	Orthoclase, Quartz } .....graphic	Orthoclase, Quartz } .....graphic
Augite or diallage	Augite or diallage ↘ Hornblende and biotite	Augite or diallage ↘ Hornblende and biotite ↘ Chlorite, epidote and carbonate
Magnetite	Magnetite	Magnetite
Ilmenite?	Ilmenite?	Ilmenite? ↘ Leucoxene
Apatite	Apatite	Apatite

blende to chlorite. What was originally labradorite is now so crowded with flakes of white mica that the twinning is hardly detectable. Another specimen from this locality also shows the plagioclase densely crowded with white mica flakes, but chlorite replaces not only original augite and biotite but in places the orthoclase of micrographic intergrowths and to some extent the micatized plagioclase. In such situations, representing the maximum of observed alteration, a clearing of the plagioclase from its minute mica flakes is

[6] Grout and Schwartz, *op. cit.*, p. 49.

observed, and the cleared feldspar, showing twinning after the albite law, is below balsam in index and is therefore albite. This secondary albite shows a pinkish color due presumably to finely divided hematite. This plus the more pronounced pink of the orthoclase gives the rock a pinkish tone.

Magnetite in the diabase seems to remain unaltered, but a few skeletal intergrowths of magnetite and leucoxene probably represent original magnetite-ilmenite intergrowths in which the ilmenite has been completely altered to leucoxene.

The principal sequences in the alteration of the granophyric diabases are shown in tabular fashion in Table 1.

The mineralogic changes summarized in Table 1 are clearly not of of the kind attributable to weathering, nor do they bear any definite relation to the surface or to superficial fracturing. This is notably true of the alteration of augite to hornblende and biotite and of these in turn to epidote. In this severely glaciated region the products of preglacial weathering have been removed, and postglacial weathering effects have been slight.

LEAST ALTERED GRANITES

LOCALITIES

Examples of the fresher granites were collected by the writer from three localities on Pigeon Point located 1–1½ miles west of Little Portage Bay. Two specimens in the University of Chicago collections, collected by the United States Geological Survey, were also studied. One was from the south shore about one-fourth of a mile west of the tip of Pigeon Point. The other was from Little Brick Island lying about a mile south of the western part of Pigeon Point.

MEGASCOPIC CHARACTERS

These rocks are fine- to medium-grained and pinkish to brick-red in color. No quartz is visible but only pink feldspars and greenish-gray ferromagnesian minerals. Some of the latter are in elongate crystals 5–8 mm. long. Some feldspars are lath-shaped and may reach 5 mm. in length.

MICROSCOPIC CHARACTERS

The microscope reveals an abundance of quartz which in some specimens is in isolated grains, in others in micrographic inter-

growth with orthoclase, and in others in both forms. Because of these variations the textures may be hypautomorphic granular (Pl. I *D*), granophyric (Pl. I *E*), or intermediate. The dominant feldspar of the rocks is orthoclase (unstriated and below balsam in index). Rarely a little microcline is present. Plagioclase, usually with little or no zoning, is subordinate and is mostly albite, though rarely as calcic as oligoclase-andesine. Both orthoclase and plagioclase are profusely flecked with minute hematite flakes to which their pink color is due.

The primary ferromagnesian mineral is usually biotite showing varying degrees of alteration to chlorite. In the specimen from Little Brick Island, hornblende is dominant and biotite subordinate. The ferromagnesian silicates are subordinate to quartz plus feldspars. Accessory minerals usually present are magnetite and apatite. In one slide pyrite was noted. In places magnetite is regularly intergrown with titanite, the latter probably an alteration from ilmenite.

MORE ALTERED GRANITES

LOCALITIES

Eight specimens of altered granites collected by the writer were studied under the microscope. Most of these were obtained inland 1–1¼ miles west of Little Portage Bay, but one was obtained on the shore one-fourth of a mile west of the tip of Pigeon Point.

MEGASCOPIC CHARACTERS

The altered granites are not different in general megascopic appearance from the fresh rocks. Their general tone is brick-red except where an unusual abundance of ferromagnesian minerals gives them a grayer tone. They are medium- to fine-grained. No quartz is visible to the unaided eye.

MICROSCOPIC CHARACTERS

Principal primary minerals are orthoclase, quartz, albite, and biotite. Accessory primary minerals are magnetite, ilmenite, and apatite, and in a few cases pyrite. The textures are commonly hypautomorphic granular.

Alterations observed in most of the granites are comparatively simple. Quartz usually shows no alteration, but in a few instances is

replaced by anthrophyllite. Orthoclase is usually not sericitized but may be replaced in varying degrees, sometimes completely, by chlorite and/or carbonate. The orthoclase of some micrographic intergrowths with quartz has been completely replaced by chlorite or by carbonate. In some specimens the ferromagnesian silicate anthrophyllite[7] in bundles or radiating aggregates has replaced orthoclase, and rarely the elongate crystals penetrate bordering quartz. Within albite flakes of white mica are developed, in places sparsely, but elsewhere abundantly. In a few places minor amounts of chlorite and carbonate are developed in the albite.

Biotite is replaced mainly by chlorite but subordinately by carbonate and epidote. Ilmenite of what were presumably grains of intergrown ilmenite and magnetite has been altered in many specimens to titanite. Pyrite grains where present have been altered peripherally to bright-red hematite.

AGENCIES OF ALTERATION

The abundant development in the alteration of the granites of fine white mica, chlorite, and epidote, and the common development of the orthorhombic amphibole, anthrophyllite, is interpreted as indicating that the alteration was largely a hydrothermal process. Weathering may have been partially responsible for the development of some secondary minerals such as calcite and leucoxene, but on these severely glaciated outcrops it is not likely to have been important.

The dominant changes chemically were: (1) Hydration as exemplified by the development of fine white mica in orthoclase and of chlorites from biotite. (2) Oxidation as exemplified in the iron-bearing silicates by the development of epidote at the expense of biotite. In biotite the iron is dominantly ferrous, in epidote dominantly ferric. Oxidation is also exemplified in the replacement of pyrite by hematite. (3) Carbonitization as exemplified by the replacement of orthoclase and biotite by carbonate.

The oxidation is believed to have been accomplished at elevated temperatures by hydrothermal solutions which probably yielded

[7] Faintly pleochroic, parallel extinction, elongate parallel to slow directions. Interference colors up to low second order.

oxygen by the dissociation of gaseous water. In accounting for the observed alterations it is not necessary to assume that these solutions contributed anything more than water, oxygen (from dissociation of water), and carbon dioxide.

ALTERATIONS OF QUARTZITES OF ROVE FORMATION NEAR THE GRANITES

The impure fine-grained quartzites of the Rove formation on Pigeon Point have been intruded by the granites. On the south shore of Pigeon Point[8] small dikes of pink granite up to 1½ inches wide cut the Rove quartzites. Many of these are sharp-walled and straight. Here also[9] pink granite exposed on the shore contains angular fragments of the Rove quartzite. A little farther west the Rove formation which dips gently to the south overlies a sill-like intrusion of granite, and near the granite contact has been converted first to a mottled rock and then to a pink rock hardly distinguishable with the unaided eye from the granite itself. These relations observed by the writer are completely accordant with those described by Grout and Schwartz.[10]

It is pertinent to this study to note the nature of the changes produced in the Rove impure quartzite by the contact effect of the granite, i.e., by solutions emanating from the granite.[11]

The least altered quartzites on the shore are blue-gray in color. A representative specimen is a very fine even-grained rock consisting dominantly of quartz in grains that tend to be equidimensional. Fairly abundant also are grains of orthoclase, chlorite, and fine flakes of white mica. The chlorite is secondary after biotite, although less biotite than chlorite remains. Some grains of albite are present. Minute grains of magnetite are accessory.

As we proceed inland toward the granite contact, the quartzite assumes a faintly pink tint and appears more vitreous, and small

[8] Three-fourths of a mile east of Little Portage Bay.

[9] One-fourth of a mile west of the southeast tip of Pigeon Point.

[10] *Op. cit.*, p. 29. They say: "As a rule the quartzite next to the red granite is reddened and injected intricately by red dikes. Such contacts are not numerous, but the red granite is clearly intrusive and includes fragments of quartzite."

[11] These changes can be well seen if one proceeds northward from the south shore of Pigeon Point from a point about a mile west of Little Portage Bay.

dikes of granitic-like material appear in it. The microscope reveals that in this rock the quartz has recrystallized into larger grains that show interlocking or sometimes have automorphic boundaries. Considerable biotite is present, though in process of alteration to chlorite. Pink orthoclase is abundant. The coarser part of this slide, showing part of a granitic veinlet, has the same minerals as the quartzite, but in addition carries an occasional grain of pink albite feldspar.

Seventy-five feet or so farther north and nearer the granite contact the quartzite becomes markedly pinkish and much of it is mottled. Bedding is still recognizable though obscured somewhat by the mottling. The redder *knoten* in this rock consist of quartz grains not irregular in outline but bounded by crystal faces against fine micrographic intergrowths of quartz and pink orthoclase that make up most of the *knoten*. Only a little orthoclase remains except in these intergrowths with quartz. Olive-green chlorite and remnants of the biotite from which it was derived are the only other abundant minerals of the *knoten*. Scattered magnetite grains are an accessory. The matrix enclosing the *knoten* consists dominantly of quartz with lesser amounts of orthoclase, grayish-green chlorite, relics of the biotite from whose alteration the chlorite was derived, and flakes of light-colored mica. Orthoclase feldspar not so pink or nearly so abundant as that of the *knoten* is also present. No plagioclase seems to be present in this rock.

As first recognized by Grout and Schwartz[12] the *knoten* in this rock afford an interesting example of micrographic intergrowths developed by contact metamorphism out of a rock in which these minerals were present as discrete grains (Pl. I *F*).

Another phase of the altered quartzite is salmon-pink in general color tone and is distinguished megascopically from the nearby granite mainly by scattered rounded *knoten* of greenish-gray color. The microscope clearly reveals the clastic and highly quartzose nature of the rock. The *knoten* are composed almost exclusively of interlocking quartz grains enclosing abundant small flakes of white mica and of chlorite, the latter secondary after biotite. The pink matrix is composed principally of quartz and pink orthoclase.

[12] *Op. cit.*, p. 56.

Chlorite and remnants of the biotite from which it was derived are also present, but it is the feldspar that gives color to the matrix. In the groundmass, also, groups of adjacent quartz grains have recrystallized to form larger units with parallel orientation throughout but showing by their lobate forms their formation out of many smaller grains.

What may be regarded as the extreme of alteration of the quartzite is represented by a rock in which greenish-gray patches up to $1\frac{1}{2}$ inches in diameter are scattered through a mottled pink and greenish-gray matrix (Pl. II *A*). The microscope shows that the large greenish-gray areas are mostly quartz and white mica as were the *knoten* in the specimen previously described. The distribution of the mica outlines a grain pattern in the quartz commensurate in coarseness with that of the rest of the rock, but scores of adjacent quartz grains have recrystallized with partial merging and parallel orientation to form quartz units of a much larger order. In these areas, minor amounts of chlorite in places take the place of white mica (see Pl. II *C*). Chlorite in larger patches also replaces biotite, remnants of which remain. The pink portions of the rock that enclose the large greenish-gray areas are an association of quartz grains with pink feldspar between them. The feldspar is mostly orthoclase but is in small part albite.

SUMMARY AND CONCLUSIONS

When allowance is made for mineralogic changes produced by metamorphic processes, the igneous rocks of Pigeon Point are easily recognizable by the aid of the microscope as belonging to a few familiar classes; granophyric diabases showing gradations into olivine diabases (that are less abundant), and medium- to fine-grained pink granites that may be granular or granophyric in texture. In the granites orthoclase is the dominant feldspar, but albite is also present; the dominant ferromagnesian mineral is biotite.

After some familiarity with these rocks has been acquired, there is little difficulty in classifying them almost instantly by the thin section as either diabases or granites in spite of the considerable metamorphism that many of them have undergone since their crystallization from the magma.

The granite is in places at least intrusive into the diabase and hence younger; the reverse relation has not been noted. The granite is clearly intrusive in the sediments of the Rove formation.

No other classes of igneous rocks were noted on Pigeon Point, with the exception of a small occurrence of anorthosite that showed transitions into granophyric diabase.

The granites, fresh or altered, are pink to brick-red in color. The little altered diabases are dark gray to greenish-gray. Certain rocks that to the unaided eye appear to be intermediate between diabases and granites, in that their texture is diabasic while their feldspar is all or in part pink, are *not* crystallizations from magmas of intermediate composition. The microscope shows that they are typical diabases that have been hydrothermally metamorphosed.

Other rocks that to the unaided eye might seem to be igneous and intermediate between diabases and granites are clearly shown by the microscope to be sediments of the pre-Cambrian Rove formation that have been altered by metamorphic processes. Many of these rocks are mottled pink and greenish, owing to a concentration of certain components in more or less rounded areas.

The metamorphic changes that have affected the igneous and sedimentary rocks of Pigeon Point are of two sorts, both attributable to igneous processes. The first type of changes was noted essentially exclusively in sediments of the Rove formation shortly above a sill-like intrusion of granite. Because of this spatial relation to the granite they are interpreted as contact-metamorphic effects produced by high-temperature solutions emanating from the granite probably at the time of its crystallization. Where their action was most severe they produced a complete recrystallization of the sedimentary rock, involving a segregation of certain of the metamorphic minerals into masses of rounded outline from a few millimeters to a few centimeters across. Quartz was recrystallized into much larger units than those typical of the unaltered sediment. Biotite, a high-temperature mineral, was abundantly developed in some of the segregations and in places micrographic intergrowths of quartz and orthoclase were abundantly formed. It is to be emphasized that the contact-metamorphic changes involved extensive recrystallization, particularly of quartz and segregations of minerals into *knoten* of a size and dis-

tribution that implies transfer of their components through distances measured in centimeters. All these changes are attributable to the adjacent granite.

What may be contact-metamorphic effects of the granite on the granophyric diabase were noted at only one place on the south shore of Pigeon Point, where granite dikes up to an inch wide traverse an unusual facies of the diabase characterized by occasional large crystals of labradorite. The augite and diallage of the diabase have in places altered first to hornblende and then to a felt of antigorite fibers.

The second type of metamorphism was hydrothermal. It succeeded the contact metamorphism just described, at how long an interval is uncertain. It was not confined to the vicinity of granite contacts but was widespread and affected diabases, the granites, and sediments of the Rove formation. Although its severity varied from place to place, few if any of the rocks of Pigeon Point seem to have wholly escaped its effects. It proceeded at lower temperatures than the contact metamorphism, as indicated by the kinds of minerals developed. Except where the alteration was extreme, it did not destroy the original texture of the igneous rock, though new minerals were substituted for old. Ophitic textures were still preserved in the altered diabases and micrographic textures in both diabases and granites. Recrystallization of quartz, so conspicuous in the contact metamorphism, was not observed in the hydrothermal metamorphism.

In the sediments the hydrothermal effects were limited largely to the development of chlorite, mainly from biotite. The alterations are best displayed in the granites and diabases where contact-metamorphic effects are absent.

The dominant components of the granites, quartz, and orthoclase appear to have been stable in the presence of the thermal solutions. Albite, a fairly abundant component, underwent slight to moderate alteration to white mica. Biotite was notably unstable and altered extensively to chlorite.

The dominant components of the diabase, augite and/or diallage, biotite, and labradorite were all notably unstable in the presence of the thermal solutions. The ferromagnesian silicates altered to chlo-

rite and epidote and the labradorite to fine white mica, probably paragonite. The subordinate and interstitial micrographic intergrowths of quartz and orthoclase were usually unaffected. In the most altered facies, chloritization, originating in the ferromagnesian silicates, began to affect the plagioclase as well, and in some places chlorite replaces the orthoclase of the micrographic intergrowths. In these late stages where chlorite is prolific, some of the micatized plagioclase alters to clear albite. Such extreme alterations obscure somewhat the original ophitic texture.

The textural evidences show that the hydrothermal alterations occurred after the complete solidification of the diabases and granites and after the contact metamorphism of the sediments. The thermal solutions probably moved upward from a deep-lying magmatic source which may well have been related to the source from which the diabase and granite magmas were derived at an earlier stage. It is perilous to speculate too closely on the nature of the magmatic source, but the fact that the hydrothermal alterations succeeded the granitic intrusions and that the diabases were notably unstable in contact with them, while the granites were relatively stable, suggests that the solutions probably came from acid rather than basic magmas.

As to the chemical nature of hydrothermal alterations, hydration was perhaps the most important and is exemplified by the development of the highly hydrous chlorites out of the anhydrous augite and the less hydrous biotite, and by the development of white mica from plagioclase and the formation of epidote. The development of carbonates in the late stages of alteration implies the presence of the carbonate radical in the solutions. The extensive replacement of labradorite by fine white mica, probably paragonite, and the eventual alteration of the latter to albite, all without change in volume, seem to imply the introduction of soda by the solutions. Certain of the alterations involved oxidation, as, for example, the development of the ferric silicate epidote from the alteration of less highly oxidized primary ferromagnesian silicates. The abundant development of fine flakes of hematite in the alteration of the plagioclase of the diabase, changing its color from gray to pink, is another evidence of oxidation of iron originally combined with less oxygen in the ferromagnesian

silicates. It is probable that dissociation of water at high temperatures furnished the oxygen for this hydrothermal oxidation.[13]

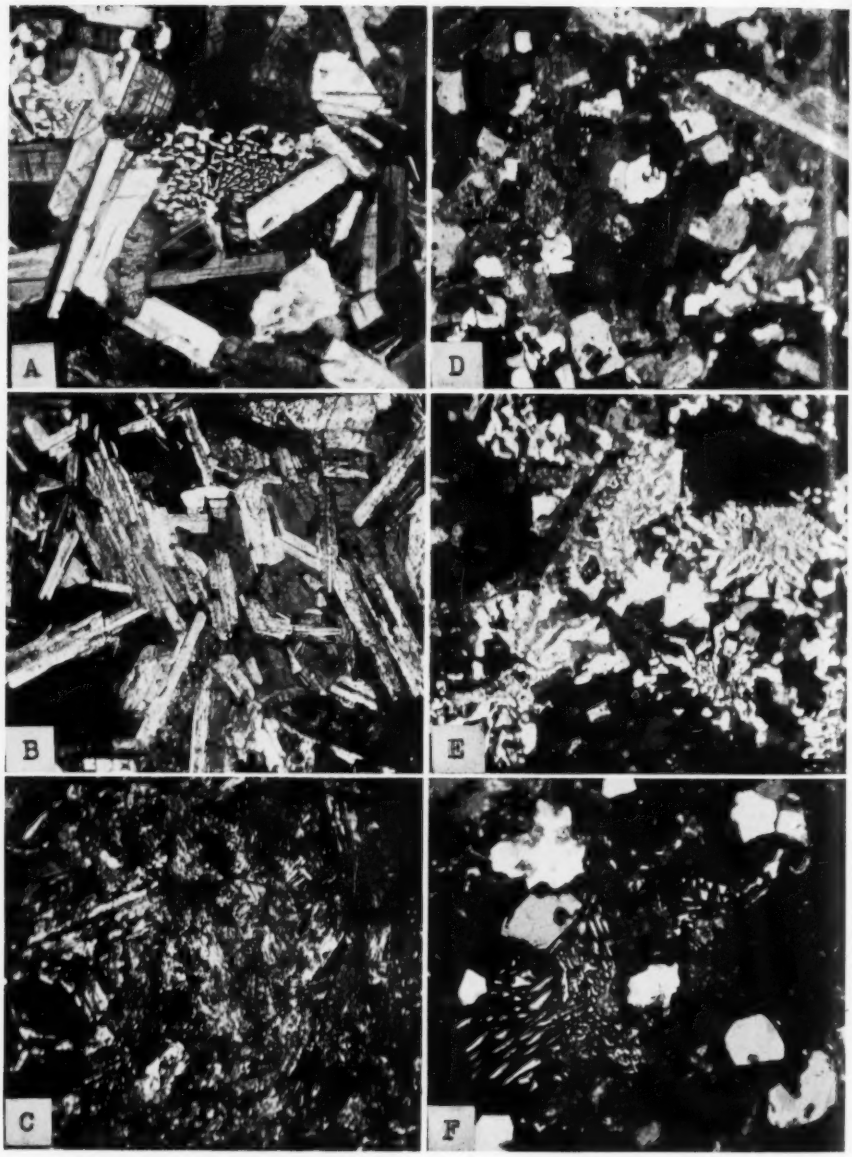
The relationships observed at Pigeon Point serve to stress the point that in the formation of many igneous rocks we must reckon not only with those processes that are operative when the material is wholly or partly liquid, but also with later changes accomplished in the completely solid rock by thermal solutions capable of penetrating them in the most intimate fashion. The student of ore deposits has long been familiar with such changes in regions of ore deposition, but they may also proceed on an important scale where unaccompanied by metallization, as has been emphasized also by Gilluly.[14]

The interpretation of the rocks intermediate in appearance between granites and diabases as rocks of these types greatly altered by later hydrothermal processes removes the principal reason for regarding the diabases and granites as differentiates *in situ* from a common magmatic parent. Final decision between differentiation *in situ* and successive intrusion first of diabase and then of granite had best await further study, but if differentiation *in situ* was the mechanism it led to a sharp differentiation of granite from diabase.

[13] J. W. Gruner, "Hydrothermal Oxidation and Leaching Experiments; Their Bearing on the Origin of Lake Superior Hematite-Limonite Ores," *Econ. Geol.*, Vol. XXV (1930), pp. 706–15.

[14] James Gilluly, "Replacement Origin of the Albite Granite near Sparta, Oregon," *U.S. Geol. Surv. Prof. Paper 175* (1933), pp. 65–81.

PLATE I



EXPLANATION OF PLATE I

(All taken in polarized light. Magnification ×12 except for *F* which is ×75.)

A. Typical fresh granophyric diabase from crest of Pigeon Point ridge about 1¼ miles east of mouth of Pigeon River

B. Little altered diabase from south shore of Pigeon Point ¼ mile west of its tip; laths of labradorite in an augite matrix; in lower center some bands in a labradorite lath are flecked with fine white mica (paragonite?), producing a mottled appearance

C. Highly altered part of the same specimen from which *B* was taken; labradorite laths are so largely altered to fine white mica that their original outlines are obscured; original augite has altered to a felt of antigorite which forms the black areas in the photograph

D. Granite from Pigeon Point about 1 mile west of Little Portage Bay, showing hypautomorphic granular texture

E. Granite from about 1½ miles west of Little Portage Bay and near top of sill shows granophyric texture

F. Graphic intergrowths of quartz and orthoclase developed by contact metamorphism in Rove impure quartzite; Pigeon Point about 1 mile west of Little Portage Bay

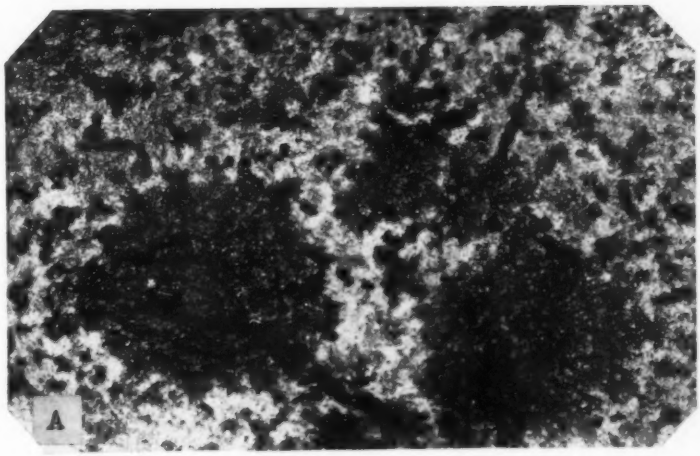
EXPLANATION OF PLATE II

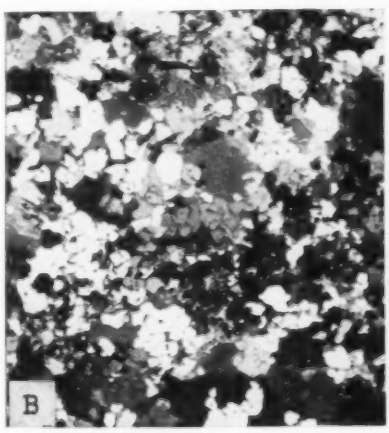
A. Impure quartzite of the Rove formation metamorphosed near a granite sill; from crest of Pigeon Point ridge about $1\frac{1}{4}$ miles west of Little Portage Bay; actually the light areas are pink and the darker areas dark greenish-gray; natural size

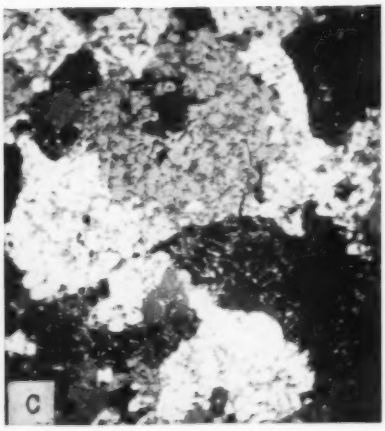
B. Microphotograph showing texture typical of the matrix of the specimen shown in *A;* the quartz is in discrete grains and the pink color is due to pink orthoclase; polarized light; magnification ×12

C. Microphotograph showing texture typical of the dark areas of the specimen shown in *A;* pink feldspar is absent; quartz has recrystallized into larger units with parallel extinction, but the original grain size is still perceivable in these units and is of the same order of magnitude as in *B*, into which *C* grades; polarized light; magnification ×12

PLATE II







THE FAUNA OF THE TYPICAL OLENTANGY SHALE[1]

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ABSTRACT

The typical outcrops of the Olentangy shale occur in central Ohio, and the term was originally confined to the formation in that area. Megascopic and microscopic fossils recently found in the Olentangy seem to tie it definitely to other more widely distributed deposits of the same stratigraphic position and to confirm its assigned place in the Middle Devonian.

The Olentangy shale as originally defined included about 30 feet of supposedly unfossiliferous argillaceous blue shale and shaly limestone belonging to the Devonian but of somewhat indeterminate correlation. It lies at the base of a shale series resting on Middle Devonian limestones. The writer extended the usage of the name to include similar but abundantly fossiliferous beds in the Lake Erie district. This seemed justified by the lithological similarity of the beds occupying essentially the same horizon and by the fact that, on very painstaking search, the Olentangy shale at the type locality did yield a few fossils of the age indicated by its stratigraphic position.

The argillaceous blue shale lying between the Delaware and the Prout (Encrinal) limestones is the unit regarded as falling under the name Olentangy shale in Ontario and northern Ohio.[2] Farther south, however, the Prout limestone pinches out, and the base of the black Ohio shale forms the upper limit of the remnant of blue shale at the type locality of the Olentangy. In Kentucky and southern Ohio this blue shale overlaps the whole earlier Devonian section and rests on rocks of Silurian age. The overlap of the Ohio shale in places extends beyond the edge of the Olentangy, and it rests on the Devonian limestones, as in the Bellefontaine outlier, or on the Silurian limestones as at Kinkead Springs, near the Ohio River. Thus the Olentangy shale is disconformable on the Delaware limestone and

[1] Presented before the Ohio Academy of Science at the Columbus meeting, May 14, 1937.

[2] C. R. Stauffer, "The Relationships of the Olentangy Shale and Associated Devonian Deposits of Northern Ohio," *Jour. Geol.*, Vol. XXIV (1916), pp. 477–79.

older formations and in turn is overlain by the Ohio shale with a disconformable contact.[3]

A somewhat different interpretation was placed on the Ohio section by Dr. Grabau, who regarded the blue Hamilton shales above the Delaware limestone in the Lake Erie district as pinching out rapidly to the south and the Olentangy as a blue-shale phase of the base of the Ohio black shale in central Ohio.[4] A major point made by Dr. Grabau is the presence of thin layers of brown to black shale interbedded with the blue shales at a number of outcrops and thus suggesting transition. At other places, however, the Olentangy-Ohio contact is sharp and irregular.[5] Moreover such brown or black shales occur 200 feet or more below the base of the Huron[6] shale in Ontario and similar shales may be found in the Hamilton beds of western New York considerably below the black shales of the Genesee. These are all Devonian shales of somewhat similar age, and the appearance of thin bands of brown to black shale certainly has no greater significance in one place than in the other. The Ontario and New York occurrences are undoubtedly within the original Hamilton and at least within the Erian group. As a matter of fact, these shaly layers, a fraction of an inch to a foot or more in thickness, which occur in many outcrops of the blue Olentangy shale of Ohio, are probably as much like the brown shales occurring in the Delaware limestone of the same region as they are like the typical Ohio or Huron shale, although perhaps less calcareous.

Bands of gray to bluish shale are not uncommon in the Ohio and Huron shales of central and northern Ohio, but they rarely show calcareous layers like those common in the typical Olentangy shale, and these gray or bluish streaks in the upper shales so far have proven barren of fossils. Nevertheless this interpretation by Dr. Grabau was accepted by R. E. Lamborn,[7] who reported several out-

[3] Stauffer, *op. cit.*, pp. 485–87.

[4] Amadeus W. Grabau, "Age and Stratigraphic Relations of the Olentangy Shale of Central Ohio, with Remarks on the Prout Limestone and So-called Olentangy Shales of Northern Ohio," *Jour. Geol.*, Vol. XXV (1917), p. 339.

[5] Stauffer, *op. cit.*, pp. 486–87.

[6] The Huron shale of Ontario and northern Ohio is the lower part of the Ohio shale of central and southern Ohio.

[7] "The Olentangy Shale in Southern Ohio," *Jour. Geol.*, Vol. XXXV (1927), pp. 721–22.

crops of shale beds at the Silurian-Devonian contact near the Ohio River as Olentangy shale, and regarded it as part of the Ohio shale.

The typical Olentangy shale crops out in Delaware and Franklin counties of central Ohio. N. H. Winchell[8] named it from the outcrops in the shaly east bank of the Olentangy River at Delaware but hesitated to extend its use beyond that region because he found no fossils in it. The wider use of the term in recent years may have been unfortunate, since its exposures are limited and its horizon is heavily drift covered both to the north and to the south of the typical outcrops in central Ohio. Certainly, the lack of adequate megascopic fossils has been a great handicap to its proper correlation. And yet the type section contains a bed of well-preserved crinoidal limestone at least 3–5 inches thick and 13 feet in extent along the cliff. This layer shows every evidence of representing the remains of a once flourishing crinoid assemblage. Many of the stems are long and lie as they fell when broken from their moorings. The crinoidal material consists of excellently preserved unweathered stems with a few plates none of which is eroded. It lies in the shales 12 feet or more above the base of the formation or any other source of residual fossils. Dr. Grabau suggested rather cautiously that this crinoidal material and other fragmentary fossils then known from the formation may have been derived from the underlying limestones.[9] It is evident, however, that he had never seen either the fossil material or the crinoid bed in outcrop, otherwise he doubtless would have recognized such a hypothesis as untenable. Other layers of limestone, somewhat lower than the crinoid bed, increased the fauna to about a half-dozen species.[10] These also are not secondary material derived from the underlying limestone but belong to the beds in which they occur, lying 3–5 feet above the base of the Olentangy shale.

A study of the conodonts from the Olentangy shale was begun in 1931, and a paper[11] was presented at the Cincinnati meeting of the

[8] "Geology of Delaware County," *Geol. Surv. Ohio*, Vol. II, Part I (1874), pp. 287–89.

[9] *Op. cit.*, p. 340.

[10] C. R. Stauffer, "The Middle Devonian of Ohio," *Geol. Surv. Ohio Bull. 10* (4th ser., 1909), p. 89.

[11] C. R. Stauffer, "Conodonts of the Olentangy Shale," *Jour. Paleon.*, Vol. XII (1938), pp. 411–43.

Paleontological Society. About a hundred of the species came from the Olentangy shale of Delaware and Franklin counties in central Ohio. During the progress of the work on the microscopic forms a large number of samples of this shale from Ontario and Ohio outcrops were washed and run through the usual routine. In addition to the numerous conodonts, various other microscopic forms were found. Among these are Polychaeta, Ostracoda, Bryozoa, fragments of graptolites, and numerous immature forms belonging to a large number of other invertebrates. Also the spore cases of plants are abundant and resemble those common in all the Devonian of the

TABLE 1

FAUNA OF THE OLENTANGY SHALE ON SLATE RUN

Sporangites huronensis Dawson	(aa)
Aulopora serpens Goldfuss	(r)
Crinoid stems and plates	(r)
Ambocoelia sp.?	(r)
Chonetes aurora? Hall	(c)
Chonetes mucronatus? Hall	(c)
Chonetes sp.	(c)
Productella spinulicosta Hall	(r)
Spirifer sp.	(r)
Strophalosia truncata (Hall)	(r)
Stropheodonta demissa? Conrad	(r)
Styliolina fissurella (Hall)	(c)
Tentaculites bellulus Hall	(a)
Tornoceras sp.	(r)
Ostracodes (a half-dozen species)	(c)
Conodonts (numerous species)	(c)
Fish plates	(r)

Lake Erie district. The samples from the gray to blue beds in the Ohio shale were barren. More significant here, however, was the finding of several thin layers of limestone with a fairly good megascopic fauna, which carries species of importance in determining the age of the Olentangy shale. This is best developed along Slate Run in Franklin County, where a thin layer of nodular limestone 17 feet below the base of the Ohio shale contains the fauna shown in Table 1.

Part of this same fauna was washed out of the shales occurring along adjacent creeks, such as Bartholomew Run, and from those in the type section at Delaware. It thus becomes evident that a diligent search of this shale will be rewarded by fossils. Moreover, the assemblage of species is a Middle Devonian fauna.

REVIEWS

Mother Earth: Being Letters on the Soil. By G. W. ROBINSON. London: T. Murby & Co., 1937. Pp. vii+202; figs. 7; pls. 1. 5*s.* 6*d.*

Professor Robinson has adopted an interesting device for presenting the story of the soil to his readers. A series of letters, addressed to R. G. Stapledon, are the vehicles of his short essays on various soil subjects. Each letter supplements the preceding one, and the story moves forward smoothly and much more informally than a straightforward series of chapters. In addition, the author's style contributes much to the literary form.

In general content the present volume is based on the author's recent treatise, *Soils, Their Origin, Constitution, and Classification*, except that the material is less severely presented. The appeal is to persons interested in the soil, not as experts, but as supplementary to their own fields. Geologists, geographers, ecologists, and others are included in this category. In all, seventeen letters are included. They begin with concepts of the soil, soil materials, humus, and soil structure. These letters are followed by others on the soil profile, types of soils, soil moisture, and the like. Toward the close of the book topics of present-day importance, such as erosion and conservation, are included.

The effectiveness of the author's presentation has been mentioned; the reviewer can heartily recommend the book to the audience to which it is addressed, as well as to the intelligent lay reader.

W. C. KRUMBEIN

"The Geology of the Rotorua-Taupo Subdivision, Rotorua and Kaimanawa Divisions," by L. I. GRANGE, in *New Zealand Geological Survey Bulletin 37* (new ser.). Wellington, 1937. Pp. 138, pls. 40, figs. 11, maps 20. Paper, 14*s.*; cloth, 16*s.*

The Rotorua-Taupo subdivision includes an area of 2,090 square miles near the center of the north island of New Zealand. It is of special interest by reason of its long record of crustal instability and vulcanism continuing up to the present time. The attendant thermal phenomena are unusually varied and spectacular, including a volcano with powerful fumaroles on its crater floor, three active volcanoes, geysers, and hot springs. Tarawera

Volcano, whose paroxysmal eruption of 1886 was an event of historic importance, lies within the area. The geology is discussed under four principal headings: (1) "Physiography and Structure," (2) "General Geology," (3) "Hot Springs and Fumaroles," (4) "Economic Geology." Excellent photographs and sketches amply support each phase of the text. A series of thirteen preliminary geologic maps accompanies the report, covering the whole area on a scale of one inch to the mile.

WILLIAM F. READ

Laboratory Exercises in Physical Geology. By WILLIAM C. PUTNAM and ROBERT W. WEBB. Stanford: Stanford University Press, 1938. 81 pages equally divided between texts and charts. $1.00.

This is a manual in which the authors have purposely omitted nearly all material which they think should be presented in the regular class lectures. In order to obtain the maximum value from these exercises the student should have a thorough understanding of the lecture material, failing which, it would be necessary to have a textbook in the laboratory at all times. No particular text is followed, and presumably the guide can be adapted to any elementary course in physical geology.

An examination of the material shows the book to be equally divided between minerals and rocks, on one hand, and the interpretation of topographic maps, on the other. The discussion on the minerals, in comparison with the remainder of the guide, is perhaps too inclusive. Little use is made of the minerals in classification of the rocks, as the rock-identification tables are fairly simple and include only the general groups.

The work on maps is well organized. The authors did not include a large number of maps for each exercise, but preferred to select a few which advantageously emphasize general aspects of each phase of the subject. The map exercises seem more adaptable to classes in physiography than to geology. The illustrations are good; the exercise sheets are well arranged.

B. T. SANDEFUR

Boletin de geologia y mineria, Vol. I, Nos. 2, 3, and 4. Caracas: Servicio Tecnico de Mineria y Geologia, Ministerio de Fomento, Venezuela, 1937. (English ed., 1938.) Pp. 314.

The present volume contains a series of thirteen contributions by various authors on the stratigraphy of Venezuela and a short paper on Pliocene and Pleistocene mammalian finds from the Barquisimeto dis-

trict. All the papers were presented before the First Geological Congress of Venezuela, which met at Caracas in February, 1937. The names of American geologists associated with petroleum companies figure prominently in the list of authors. The areas described lie chiefly in the petroliferous terrains of the Maracaibo and Caribbean coastal belt; a few fall within the basin of the Orinoco River, south of the coast ranges. The areal geology, stratigraphic sequence, paleontology, lithology, and structural relations of each area are described in more or less detail, with numerous photographs, sketch maps, and sections. Little attention is paid to the broader problems of stratigraphic correlation and historical geology. A preliminary geological map of the area between the Orinoco River and the coast has been compiled and accompanies the regional reports. The distribution of Tertiary sediments by epochs, together with the Cretaceous, and "pre-Cretaceous," is outlined on a scale of about twenty-five miles to the inch.

WILLIAM F. READ

"The Geology of Texas," Vol. II: "Structural and Economic Geology," by E. H. SELLARDS and C. L. BAKER, *University Texas Bull. 3401*. Austin, Tex., 1935. Pp. 880; pls. 8; figs. 40.

This 880-page volume contains 210 pages of structural geology, 410 pages of general information on economic geology, and 260 pages of special reports on ore and salt deposits. Structural features east of the Pecos River are described by Sellards; those west of the Pecos, by Baker. Sellards groups the major structures of his territory into a number of provinces for convenience in discussing their historical development. Baker's area is small enough to be regarded as a single complex province. To interrelate the histories of these several provinces and to place them in proper perspective relative to the larger aspects of continental evolution, a preliminary outline of the major deformations affecting Texas as a whole is presented. A structure-contour map of Texas on the scale of 1:1,000,000 accompanies the text. Full references to source material appear in the footnotes.

A survey of the mineral resources of Texas is presented by Baker. Petroleum and substances related to petroleum are, however, reserved for separate treatment at some future date. The other important geologic resources of the state, including coal and water supply, are covered here. The discussion of a typical product may include a description of its mode of occurrence, its various uses, a note on world-production and markets,

the nature of deposits found in Texas, the extent of their development, and brief mention of deposits in other parts of the world—all amply documented with full references. Naturally, the amount and nature of information which the author considers relevant to a summary of this kind vary considerably with different products.

The special reports include "The Iron Ores of East Texas," by Edwin B. Eckel and Paul E. M. Purcell (20 pages); "Preliminary Report on the Terlingua Quicksilver District," by Clyde P. Ross (10 pages); "Preliminary Report on the Shafter Mining District," by Clyde P. Ross and W. E. Cartwright (34 pages); "The Texas–New Mexico Potash Deposits," by G. G. Mansfield and W. B. Lang (193 pages; there are 131 pages of analyses of well cuttings); and "The Potassium Sulfate Mineral Polyhalite in Texas," by W. A. Cunningham (35 pages).

WILLIAM F. READ

"Contributions to Virginia Geology," in *Virginia Geological Survey Bulletin 46*. University, Va., 1936. Pp. 211; pls. 22; figs. 10.

Bulletin 46 of the Virginia Geological Survey contains thirteen contributions by as many authors. Two of the longer papers deal with the stratigraphy and structure of small areas in the Valley and Ridge Province. Another discusses the stratigraphy of Ordovician bentonite horizons in the southwestern portion of the state. A fourth submits new evidence bearing on the origin of the Natural Bridge of Virginia. Of the nine shorter papers, none exceeds a dozen pages in length. One is a brief, semipopular account of the physiographic features of the state and the manner of their development. Three are concerned with economic problems: petroleum possibilities near the Kentucky border; the origin of Oriskany iron and manganese ores; and the mineralogy of certain Virginia marbles. Two are of a historical nature, dealing with the contributions of W. B. Rogers to Virginia geology and the importance of Virginia's mineral resources to the cause of the Confederacy during the Civil War. The three remaining papers are concerned with local phenomena of geological interest: a siphon spring flowing only at regular intervals; a mountain lake dammed by landslips; the humidity and waters of a limestone cavern.

Of the thirteen authors whose contributions appear in this bulletin, four are members of the Virginia Geological Survey; six are connected with academic institutions in the same state; and three are members of universities outside Virginia.

WILLIAM F. READ

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